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16. ABSTRACT

Selection and design of cover for solid/hazardous waste usually require engineering planning for efficient accommodation of the volume of incoming waste within certain moderate to severe constraints. The foremost constraints are usually the amount and characteristics of cover material available in the immediate vicinity. Local soils available in adequate amounts seldom have the best characteristics for the several cover functions, e.g., they are too clayey or sandy. Several steps are recommended for effective planning of cover. First, identify the primary and secondary functions to be served by the cover and establish relative importances, e.g., impeding water percolation is more important than supporting vegetation, etc. Second, use data on soil properties in terms of the Unified Soil Classification or the U.S. Department of Agriculture systems to rate available soil for effectiveness in the various functions. Third, specify certain design procedures in the disposal operation for circumventing the deficiencies of the selected cover soil. Placement procedures, such as compaction, will improve the soil for certain functions. Elsewhere, the soil properties favorable for one function are unfavorable for another, e.g., a clayey cover soil impeding water percolation will prevent leakage of decomposition gases that may also be desired. Fourth, where a single soil cannot serve contrasting cover functions, the designer may incorporate features, such as layering, or can resort to the use of special non-soil materials and additives.

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by

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Interagency Agreement No. EPA-IAG-D7-01097

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FOREWORD

The Environmental Protection Agency (EPA) was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollution discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research, a most vital communication's link between the researcher and the user community.

This report is a result of research supported by the EPA to obtain engineering information essential to the design of cover materials for landfills. Proper selection and placement of these materials will aid in the prevention of leachate generation.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

Selection and design of cover for solid/hazardous waste landfills usually require engineering planning for efficient accommodation of the volume of incoming waste within certain moderate to severe constraints. The foremost constraints are usually the amount and characteristics of cover material available in the immediate vicinity. Local soils available in adequate amounts seldom have the best characteristics for the several cover functions, e.g., they are too clayey or sandy.

Several steps are recommended for effective planning of cover. First, identify the primary and secondary functions to be served by the cover and establish relative importances, e.g., impeding water percolation is more important than supporting vegetation, etc. Second, use data on soil properties in terms of the Unified Soil Classification or the U. S. Department of Agriculture systems to rate available soil for effectiveness in the various functions. Third, specify certain design procedures in the disposal operation for circumventing the deficiencies of the selected cover soil. Placement procedures, such as compaction, will improve the soil for certain functions. Elsewhere, the soil properties favorable for one function are unfavorable for another, e.g., a clayey cover soil impeding water percolation will prevent leakage of decomposition gases that may also be desired. Fourth, where a single soil cannot serve contrasting cover functions, the designer may incorporate features, such as layering, or can resort to the use of special non-soil materials and additives.

This report was submitted in fulfillment of Phases I and II of Interagency Agreement No. EPA-IAG-D7-01097 between the U. S. Environmental Protection Agency and the U. S. Army Engineer Waterways Experiment Station (WES). Work for this manual was conducted during the period March 1977 to December 1978, and work was completed in December 1978. Dr. R. J. Lutton, Geotechnical Laboratory, WES, was principal investigator and author. Mr. G. L. Regan, WES, coauthored an interim report, and Dr. L. W. Jones, University of Tennessee, prepared most of Section 19. Director of WES during the work period was COL John L. Cannon, CE. Technical Director was Mr. F. R. Brown.

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LIST OF ABBREVIATIONS AND SYMBOLS*

ABBREVIATIONS

AASHTO	-- American Association of State Highway and Transportation Officials
AET	-- actual evapotranspiration
AMC	-- antecedent moisture condition
Ann.	-- annual
ASTM	-- American Society for Testing and Materials
°C	-- degrees Celsius
CI	-- cone index
CN	-- curve number (for calculating runoff)
CU	-- consumptive use
cfs	-- cubic feet per second
cm	-- centimeter
cm/hr	-- centimeters per hour
cm/m	-- centimeters per meter
cm/s	-- centimeters per second
cm/sec	-- centimeters per second
deg	-- degrees
diam	-- diameter
EI	-- erosion index
EPA	-- Environmental Protection Agency
ERCI	-- effective rating cone index
FS	-- factor of safety
°F	-- degrees Fahrenheit
ft	-- foot

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* Abbreviations and symbols explained on tables and figures and not used in text are not repeated here.

ABBREVIATIONS AND SYMBOLS (continued)

ft^3/min -- cubic feet per minute
gal -- gallon
gal/yd^2 -- gallons per square yard
gm -- gram
gm/cm^2 -- grams per square centimeter
gm/min -- grams per minute
H -- horizontal
I -- infiltration
in. -- inch
in./ft -- inches per foot
in./hr -- inches per hour
kg -- kilogram
ksf -- kips per square foot
lb -- pound
lb/ft^2 -- pounds per square foot
lb/ft^3 -- pounds per cubic foot
lb per cu ft -- pounds per cubic foot
lb/yd^2 -- pounds per square yard
lb/yd^3 -- pounds per cubic yard
LGP -- low ground pressure (vehicle)
LL -- liquid limit
Mth. -- monthly
m -- meter
mil -- mil
mm -- millimeter
mm/hr -- millimeters per hour
mph -- miles per hour
P -- precipitation
PET -- potential evapotranspiration
PI -- plasticity index
PL -- plastic limit
PRC -- percolation
pcf -- pounds per cubic foot
pH -- hydrogen ion concentration

ABBREVIATIONS AND SYMBOLS (continued)

psf -- pounds per square foot
psi -- pounds per square inch
Q -- unconsolidated-undrained triaxial compression (test)
R -- consolidated-undrained triaxial compression (test)
RCI -- rating cone index
RI -- remolding index
RO -- runoff
RPM -- revolutions per minute
S -- consolidated-drained triaxial compression (test)
SCS -- Soil Conservation Service
SI -- slope index
SL -- shrinkage limit
ST -- storage
ΔST -- change in storage
USC -- unified soil classification
USCS -- Unified Soil Classification System
USDA -- United States Department of Agriculture
USLE -- universal soil loss equation
V -- vertical
VCI -- vehicle cone index
WEE -- wind erosion equation
yd -- yard
$\#/ft^3$ -- pounds per cubic foot

SYMBOLS

A -- area; average water erosion soil loss
A' -- average wind erosion soil loss
A'_1 -- erodibility increment for dry aggregate
A'_2 -- erodibility increment for T'
A'_3 -- erodibility increment for C'
A'_4 -- erodibility increment for L'
A'_5 -- erodibility increment for V'
a -- subscript in chemical formula; factor in infiltration equation
b -- subscript in chemical formula; slope vertical to horizontal
C -- carbon; cover/management factor; watershed/storm coefficient

ABBREVIATIONS AND SYMBOLS (continued)

C_c -- compression index
C_o -- gas concentration
C' -- climatic factor
CH_4 -- methane gas
CO_2 -- carbon dioxide gas
c -- rate of infiltration decrease; subscript in chemical formula; soil cohesion
c_D -- developed soil cohesion
c_v -- coefficient of consolidation
c' -- effective soil cohesion
D -- foundation layer thickness
D_o -- free space gas diffusivity
D_p -- gas diffusivity of porous media
D_{15} -- soil grain size where 15 percent by weight is finer
D_{85} -- soil grain size where 85 percent by weight is finer
d -- subscript in chemical formula; day
E -- rainfall kinetic energy
e -- void ratio; Napierian base; subscript in chemical formula
e_o -- initial void ratio
F -- force
f -- infiltration rate; infiltration capacity
f_c -- final infiltration rate
f_o -- initial infiltration rate
f_1 -- soil infiltration rate after 1 hour continuous rainfall
f_{1v} -- infiltration rate of vegetated soil
$f(-)$ -- function of (-)
G_s -- specific gravity of solids
GI -- growth index of vegetation
H -- hydrogen; height; drainage length
ΔH -- change in height
H_c -- capillary head
H_t -- total initial thickness
H_2S -- hydrogen sulfide gas
I -- maximum 30-minute rainfall intensity
i -- average rainfall intensity; hydraulic gradient

ABBREVIATIONS AND SYMBOLS (continued)

K -- soil erodibility factor; potassium
K' -- soil erodibility index
K_A -- coefficient of active earth pressure
K_2O -- potassium oxide
k -- coefficient of permeability; hydraulic conductivity
L -- cover thickness; slope-length factor
L' -- length in prevailing wind direction
LS -- topographic factor combining length and steepness effects
N -- empirical vegetation cover factor; nitrogen
N_K -- stability number
NH_3 -- ammonia gas
n -- porosity
O -- oxygen
P -- practice factor; phosphorus
p -- pressure
ΔP -- total load
P'_o -- average initial effective stress
P_2O_5 -- phosphorus pentoxide
Q -- quantity of water; gas production rate
q -- rate of flow; rate of discharge
R -- rainfall and runoff erosivity index
S -- sulfur; degree of saturation; slope-steepness factor; soil shear strength
S_a -- available storage of water
T' -- soil ridge roughness factor
T_v -- consolidation time factor
t -- time
u -- pore water pressure
V' -- equivalent vegetative cover
v -- wind velocity
W -- weight force
w -- weight water content; coefficient in chemical formula
x -- coefficient in chemical formula
y -- coefficient in chemical formula
z -- coefficient in chemical formula; depth

ABBREVIATIONS AND SYMBOLS (continued)

β -- slope inclination

γ -- unit weight of soil

γ_d -- dry unit weight (or dry density)

γ_m -- wet unit weight (or wet density)

γ_w -- unit weight of water

Θ -- volumetric water content

σ -- normal stress on shear surface

σ_1 -- major principal stress

σ_3 -- minor principal stress (chamber pressure)

ϕ -- angle of internal friction

ϕ' -- effective angle of internal friction

ϕ_D -- developed angle of internal friction

$>$ -- greater than

$<$ -- less than

$>>$ -- much greater than

METRIC CONVERSION TABLE

Multiply	By	To Obtain
acres	4046.856	square meters
atmospheres	101.325	kilopascals
cubic feet per second	0.02831685	cubic meters per second
cubic yards	0.7645549	cubic meters
degrees (angle)	0.01745329	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
feet	0.3048	meters
gallons (U. S. liquid)	0.003785412	cubic meters
gallons (U. S. liquid) per square yard	4.5273	cubic decimeters per square meter
inches	0.0254	meters
inches per hour	0.0254	meters per hour
kips (force)	4.448222	kilonewtons
miles (U. S. statute)	1.609344	kilometers
miles (U. S. statute) per hour	1.609344	kilometers per hour
mils	0.0254	millimeters
pounds (force) per square foot	47.88026	pascals
pounds (force) per square inch	6894.757	pascals
pounds (mass)	0.4535924	kilograms
pounds (mass) per acre	0.1120851	grams per square meter
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter

(Continued)

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* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

METRIC CONVERSION TABLE (Continued)

Multiply	By	To Obtain
pounds (mass) per cubic yard	0.593276	kilograms per cubic meter
square feet	0.09290304	square meters
square inches	6.4516	square centimeters
square miles	2.589988	square kilometers
tons (force) per square foot	95.76052	kilopascals
tons (short, mass)	907.1847	kilograms
tons (mass) per acre	0.2241702	kilograms per square meter
yards	0.9144	meters

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SECTION 1

INTRODUCTION

Each year in the United States, approximately three billion tons of solid wastes are generated[1] as follows:

Mining	1,890,000,000 tons	63 percent
Agricultural	660,000,000 tons	22 percent
Industrial	270,000,000 tons	9 percent
Municipal	150,000,000 tons	5 percent
Sewage	30,000,000 tons	1 percent

Industrial and municipal wastes constitute a small proportion on a relative basis, but the annual tonnages are staggering when the pollution potential is considered.

Much solid waste is disposed on land behind dikes or by land burial, in conflict with growing limitations on land availability. Economical use of land space and growing concern for the preservation of a healthful environment and our future were important factors in the enactment of Public Law 94-580,[2] "Resource Conservation and Recovery Act of 1976" (21 October 1976). The act provides for "promulgation of guidelines for solid waste collection, transport, separation, recovery, and disposal practices and systems...," and calls for development and publication of guidelines for solid waste management.

PURPOSE OF STUDY

This study was intended to provide a basis for development of guidelines in selection, design, and construction of cover for management of municipal, industrial, and hazardous solid wastes (with the exception of radioactive waste). The manual describes and evaluates various cover materials and presents cover design procedures relative to specific functional requirements and controlling physical phenomena to aid permit writers, designers, and others seeking the most effective solutions to problems of burial of solid waste.

SCOPE OF MANUAL

Natural soils as cover are the principal subject; however, synthetic membranes, chemicals, and waste products are also discussed in detail since their relative importance should grow in the future. Each of the important functions of cover is considered in the context of selecting and designing cover but with cognizance of the effects of conflicts that may arise, e.g., between water infiltration and gas venting. A scheme is proposed for establishing functional priorities and in turn for weighting the importance of soil characteristics to allow for most effective selection. Allowance is made for functional conflicts through design features. Procedures are presented for designing soil cover systems to meet the requirements based on principles of soil mechanics and the state of the art in soil construction. Accordingly, this manual is not so much a review of current methods as it is a guide to potentially the best practice.

BACKGROUND

Preliminary investigations for solid waste disposal operations are summarized briefly here, whereas a review of all aspects of solid waste disposal in sanitary landfills is available elsewhere.[3,4] During preliminary investigations the potential sites are chosen and the local geology is determined. The subsurface may be explored at two or three most likely sites. Subsurface exploration is accomplished by trenching or boring, and soil samples are usually obtained for laboratory testing. Preliminary investigations can be particularly important to hazardous waste disposal in view of the serious consequences of leakage.

One purpose of preliminary site investigations is to ascertain the subsurface conditions of each potential site. The geology should be favorable to minimizing the environmental impact of the disposal project on surrounding water supplies, i.e., not significantly altering water quality. Another purpose locally is to evaluate supportive qualities of the foundation soil where the cover side slope constitutes a dike retaining potentially unstable waste. Subsurface exploration should provide soil samples representative of the soil types and stratification. Final site selection is ordinarily based on the type of waste disposal area (e.g., landfill versus trench operation), favorable topography, favorable geological and groundwater conditions, public acceptance, and availability of adequate amounts of cover materials with necessary properties for minimizing objectionable environmental effects.

Geologic and subsurface sampling and exploration may also be conducted on potential off-site borrow areas, which might provide suitable soil for cover. Investigations should be sufficient to define the soil types and quantities and natural water contents. Laboratory testing may also include classification and compaction tests and, if necessary, tests for permeability and strength properties in compacted samples.

SOIL CLASSIFICATION SYSTEM

A soil classification system categorizes soil according to general, but somewhat arbitrary, groups possessing similar properties. These properties may be from an engineering or an agricultural point of view.

Currently, soils used in solid waste disposal design and construction are classified[5] according to either the Unified Soil Classification System (USCS) or the U. S. Department of Agriculture (USDA) Classification System. The USCS (Figure 1) is engineering oriented; soils are grouped according to gradation of particle sizes; to percentages of gravel, sand, and fines; and to plasticity characteristics. The USDA system (Figure 2) classifies on the basis of texture only, i.e., percentages of gravel, sand, silt, and clay. Figure 3 emphasizes the grain-size differences between the USDA and USC systems. Figure 4 presents relationships between the two systems based on laboratory tests on hundreds of soil samples. Simplified listings of classification interchangeability are given in Tables 1 and 2.

A nationwide study[5] of soils being used for covering solid waste obtained a sample that clearly suggests their diversity. Sixty-three cover soils (or sets of samples) from sanitary landfills were collected and tested in the laboratory. The objective of sampling was to develop a nationwide cross section of usable soil, but no statistical representation of relative importances was intended. The frequency of occurrence in this study was as follows:

Soil Type	Occurrences	Soil Type	Occurrences
GP	1	SM-SC	1
GM	2	SC	2
SW	5	ML	5
SW-SM	5	CL	15
SP	1	OL	1
SP-SM	1	MH	2
SM	16	CH	4

Two other soils not classified are probably CL by description.

Twenty of the 34 coarse-grained soils were gravelly though this component was not always explicitly included in the USCS designation. The scarcity of soils designated GC and SC is considered to be misleading since these soils are usable and fairly common.

Adding to the complexity is the occurrence of more than one soil type at a site, with attendant complexities from mixtures or heterogeneity. Also, some variability in important characteristics within one type may be expected. Refer to COVER COMPACTION in Section 5 for further discussion of variability of soil manifested in variable compaction test results.

NATURE OF SOLID WASTE

Solid wastes range over a considerable spectrum; and a manual such as this, applicable to all types, is necessarily lengthy and complicated. Fortunately, the designer of a cover for a specific site can usually narrow his range of interest to one of several solid waste types and can gloss over certain other parts of this manual that obviously are inapplicable. Four logical classes of solid waste from an engineering viewpoint are solid municipal, high-solids industrial, saturated industrial, and rubble wastes. Hazardous waste in barrels or other rigid containers constitutes a fifth class with special problems requiring special attention.

Solid municipal waste (excluding sewage sludge) comes directly from home and business collections and consists of a mixture of materials of great diversity. Table 3 shows approximate makeup of typical municipal waste. In greater detail one might find tree branches, auto tires, partially filled

Major Divisions			Group Symbols	Typical Names	Field Identification Procedures (Excluding particles larger than 3 in. and basing fractions on estimated weights)		
1	2		3	4	5		
Coarse-grained Soils More than half of material is larger than No. 200 sieve size. The No. 200 sieve size is about the smallest particle visible to the naked eye.	Gravels More than half of coarse fraction is larger than No. 4 sieve size. (For visual classification, the 1/4-in. size may be used as equivalent to the No. 4 sieve size)	Clean Gravels (Little or no fines)	GW	Well-graded gravels, gravel-sand mixtures, little or no fines.	Wide range in grain sizes and substantial amounts of all intermediate particle sizes.		
			GP	Poorly graded gravels or gravel-sand mixtures, little or no fines.	Predominantly one size or a range of sizes with some intermediate sizes missing.		
		Gravels with Fines (Appreciable amount of fines)	GM	Silty gravels, gravel-sand-silt mixture.	Nonplastic fines or fines with low plasticity (for identification procedures see ML below).		
			GC	Clayey gravels, gravel-sand-clay mixtures.	Plastic fines (for identification procedures see CL below).		
	Sands More than half of coarse fraction is smaller than No. 4 sieve size.	Clean Sands (Little or no fines)	SW	Well-graded sands, gravelly sands, little or no fines.	Wide range in grain size and substantial amounts of all intermediate particle sizes.		
			SP	Poorly graded sands or gravelly sands, little or no fines.	Predominantly one size or a range of sizes with some intermediate sizes missing.		
		Sands with Fines (Appreciable amount of fines)	SM	Silty sands, sand-silt mixtures.	Nonplastic fines or fines with low plasticity (for identification procedures see ML below).		
			SC	Clayey sands, sand-clay mixtures.	Plastic fines (for identification procedures see CL below).		
Fine-grained Soils More than half of material is smaller than No. 200 sieve size.					Identification Procedures on Fraction Smaller than No. 40 Sieve Size		
					Dry Strength (Crushing characteristics)	Dilatancy (Reaction to shaking)	Toughness (Consistency near PL)
	Silts and Clays Liquid limit is less than 50		ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity.	None to slight	Quick to slow	None
			CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays.	Medium to high	None to very slow	Medium
			OL	Organic silts and organic silty clays of low plasticity.	Slight to medium	Slow	Slight
	Silts and Clays Liquid limit is greater than 50		MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts.	Slight to medium	Slow to none	Slight to medium
			CH	Inorganic clays of high plasticity, fat clays.	High to very high	None	High
			OH	Organic clays of medium to high plasticity, organic silts.	Medium to high	None to very slow	Slight to medium
Highly Organic Soils			Pt	Peat and other highly organic soils.	Readily identified by color, odor, spongy feel and frequently by fibrous texture.		

(1) Soils possessing characteristics of two groups are designated by combinations of group symbols. For example GW-GC, well-graded gravel-sand mixture with clay binder. (2) All sieve sizes on this chart are U. S. standard.

FIELD IDENTIFICATION PROCEDURES FOR FINE-GRAINED SOILS OR FRACTIONS (MINUS NO. 40 SIEVE)

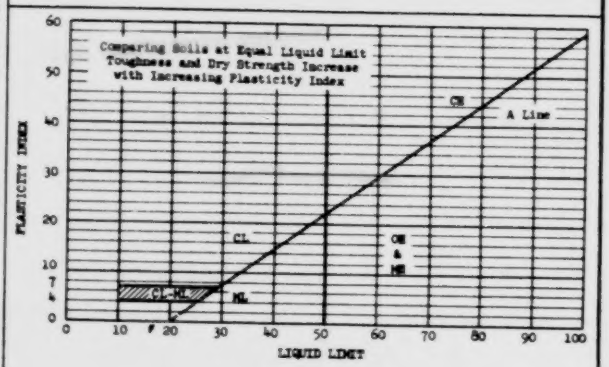
Screening is not intended; simply remove by hand the coarse particles that interfere with tests.

Dilatancy (reaction to shaking). After removing particles larger than No. 40 sieve size, prepare a pat of moist soil with a volume of about one-half cubic inch. Add enough water if necessary to make the soil soft but not sticky. Place the pat in the open palm of one hand and shake horizontally, striking vigorously against the other hand several times. A positive reaction consists of the appearance of water on the surface of the pat which changes to a livery consistency and becomes glossy. When the sample is squeezed between the fingers, the water and gloss disappear from the surface, the pat stiffens, and finally it cracks or crumbles. The rapidity of appearance of water during shaking and of its disappearance during squeezing assist in identifying the character of the fines in a soil. Very fine clean sands give the quickest and most distinct reaction whereas a plastic clay has no reaction. Inorganic silts, such as a typical rock flour, show a moderately quick reaction.

Dry Strength (crushing characteristics). After removing particles larger than No. 40 sieve size, mold a pat of soil to the consistency of putty, adding water if necessary. Allow the pat to dry completely by oven, sun, or air-drying, and then test its

Figure 1. Summary of the USC system.

(continued)

<table>
<tr><th>Information Required for Describing Soils</th><th colspan="4">Laboratory Classification Criteria</th></tr>
<tr><td>6</td><td colspan="4">7</td></tr>
<tr><td rowspan="8">For undisturbed soils add information on stratification, degree of compactness, cementation, moisture conditions, and drainage characteristics.
Give typical name; indicate approximate percentages of sand and gravel, maximum size; angularity, surface condition, and hardness of the coarse grains; local or geologic name and other pertinent descriptive information; and symbol in parentheses.
Example:
Silty sand, gravelly; about 20% hard, angular gravel particles 1/2-in. maximum size; rounded and subangular sand grains, coarse to fine; about 15% nonplastic fines with low dry strength; well compacted and moist in place; alluvial sand; (SM).</td><td rowspan="10">Use grain-size curve in identifying the fractions as given under field identification.</td><td rowspan="8">Determine percentages of gravel and sand from grain-size curve. Depending on percentage of fines (fraction smaller than No. 200 sieve size) coarse-grained soils are classified as follows:
Less than 5% = GW, GP, SW, SP,
More than 12% = GM, GC, SM, SC.
5% to 12% = Borderline cases requiring use of dual symbols.</td><td colspan="2">$C_u = \frac{D_{60}}{D_{10}}$ Greater than 4
$C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3</td></tr>
<tr><td colspan="2">Not meeting all gradation requirements for GW</td></tr>
<tr><td>Atterberg limits below "A" line or PI less than 4</td><td rowspan="2">Above "A" line with PI between 4 and 7 are borderline cases requiring use of dual symbols.</td></tr>
<tr><td>Atterberg limits above "A" line with PI greater than 7</td></tr>
<tr><td colspan="2">$C_u = \frac{D_{60}}{D_{10}}$ Greater than 6
$C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3</td></tr>
<tr><td colspan="2">Not meeting all gradation requirements for SW</td></tr>
<tr><td>Atterberg limits below "A" line or PI less than 4</td><td rowspan="2">Above "A" line with PI between 4 and 7 are borderline cases requiring use of dual symbols.</td></tr>
<tr><td>Atterberg limits above "A" line with PI greater than 7</td></tr>
<tr><td></td><td colspan="3"></td></tr>
<tr><td>For undisturbed soils add information on structure, stratification, consistency in undisturbed and remolded states, moisture and drainage conditions.
Give typical name; indicate degree and character of plasticity; amount and maximum size of coarse grains; color in wet condition; odor, if any; local or geologic name and other pertinent descriptive information; and symbol in parentheses.
Example:
Clayey silt, brown; slightly plastic; small percentage of fine sand; numerous vertical root holes; firm and dry in place; loess; (ML).</td><td colspan="3">
PLASTICITY CHART
For laboratory classification of fine-grained soils</td></tr>
</table>

strength by breaking and crumbling between the fingers. This strength is a measure of the character and quality of the colloidal fraction contained in the soil. The dry strength increases with increasing plasticity.

High dry strength is characteristic of clays of the CH group. A typical inorganic silt possesses only very slight dry strength. Silty fine sands and silts have about the same slight dry strength, but can be distinguished by the feel when powdering the dried specimen. Fine sand feels gritty whereas a typical silt has the smooth feel of flour.

Toughness (consistency near plastic limit). After particles larger than the No. 40 sieve size are removed, a specimen of soil about one-half inch cube in size is molded to the consistency of putty. If too dry, water must be added and if sticky, the specimen should be spread out in a thin layer and allowed to lose some moisture by evaporation. Then the specimen is rolled out by hand on a smooth surface or between the palms into a thread about one-eighth inch in diameter. The thread is then folded and rerolled repeatedly. During this manipulation the moisture content is gradually reduced and the specimen stiffens, finally loses its plasticity, and crumbles when the plastic limit is reached.

After the thread crumbles, the pieces should be lumped together and a slight kneading action continued until the lump crumbles.

The tougher the thread near the plastic limit and the stiffer the lump when it finally crumbles, the more potent is the colloidal clay fraction in the soil. Weakness of the thread at the plastic limit and quick loss of coherence of the lump below the plastic limit indicate either inorganic clay of low plasticity, or materials such as kaolin-type clays and organic clays which occur below the A-line.

Highly organic clays have a very weak and spongy feel at the plastic limit.

Figure 1. (continued)

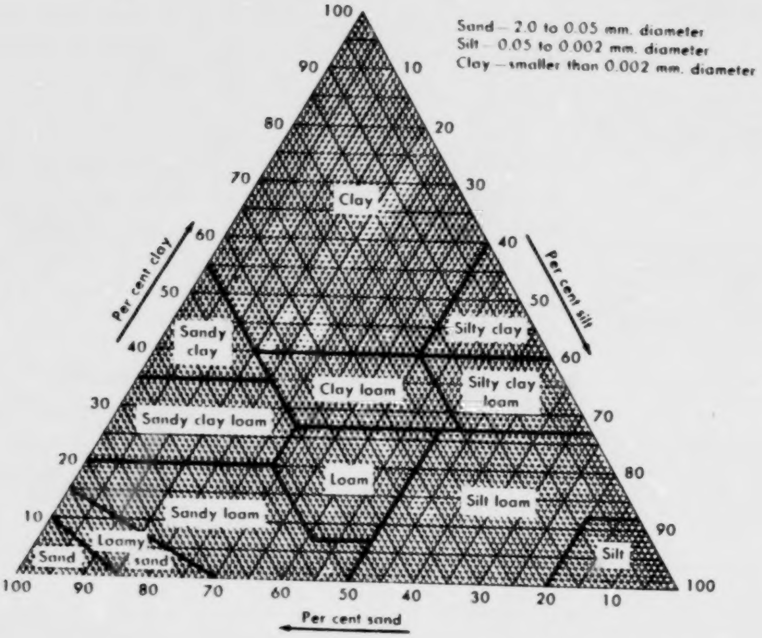

Sand — 2.0 to 0.05 mm. diameter
Silt — 0.05 to 0.002 mm. diameter
Clay — smaller than 0.002 mm. diameter
Per cent clay
Per cent silt
Per cent sand
100
90
80
70
60
50
40
30
20
10
Clay
Sandy clay
Silty clay
Clay loam
Silty clay loam
Sandy clay loam
Loam
Sandy loam
Silt loam
Loamy sand
Sand
Silt

Figure 2. USDA textural classification chart.

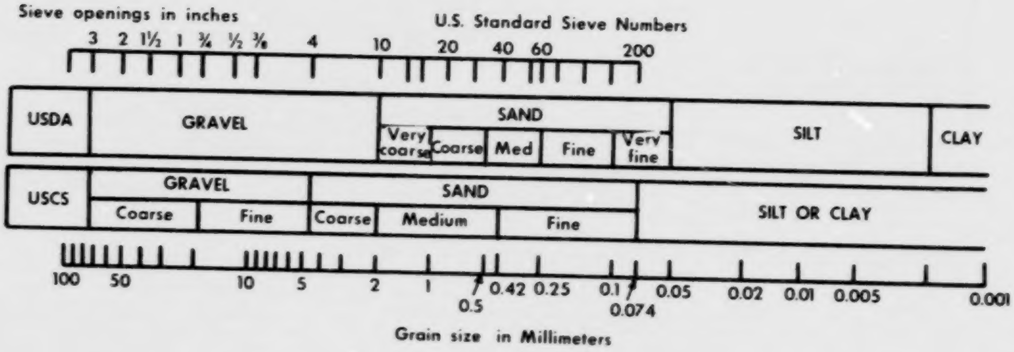

Sieve openings in inches
3
2
1½
1
¾
½
⅜
U.S. Standard Sieve Numbers
4
10
20
40
60
200
USDA
GRAVEL
SAND
Very coarse
Coarse
Med
Fine
Very fine
SILT
CLAY
USCS
GRAVEL
Coarse
Fine
SAND
Coarse
Medium
Fine
SILT OR CLAY
100
50
10
5
2
1
0.5
0.42
0.25
0.1
0.074
0.05
0.02
0.01
0.005
0.001
Grain size in Millimeters

Figure 3. Comparison of USCS and USDA particle-size scales.

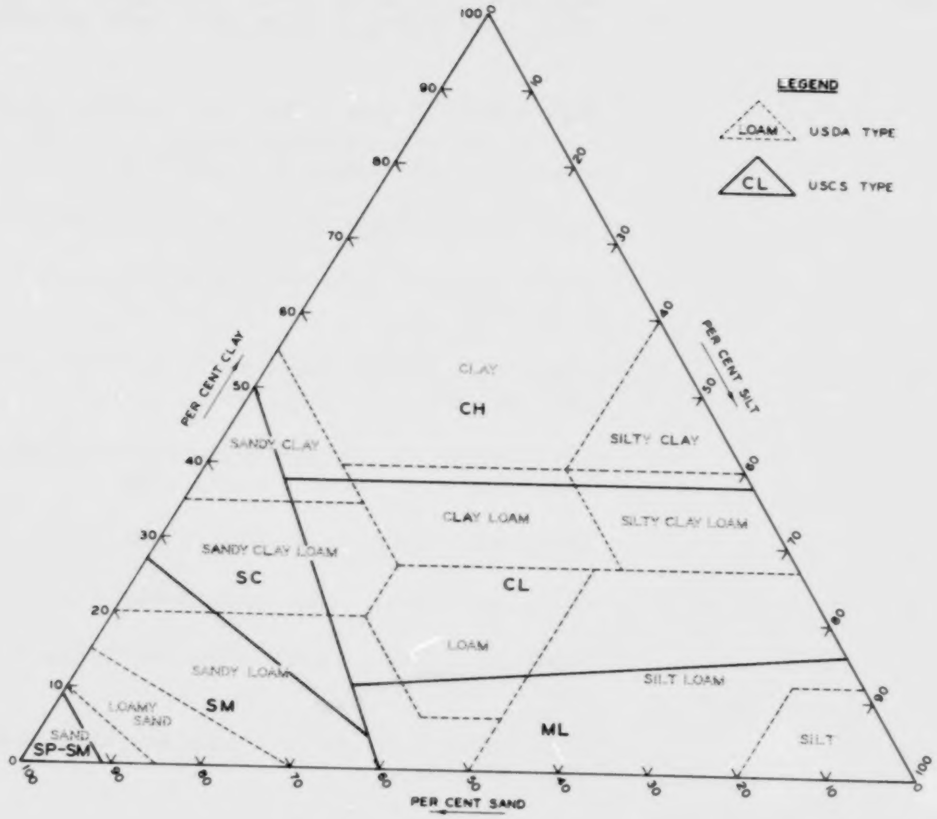


Figure 4. USCS soils superimposed on the USDA textural classification chart.[6] (Correlations are only approximate.)

TABLE 1. USDA TEXTURAL TYPES CORRESPONDING TO USCS SOIL DESIGNATIONS

USCS Soil Type	USDA Soil Types
GW	Same as GP (except well graded in grain sizes)
GP	Gravel, very gravelly sand (less than 5 percent silt and clay)
GM	Very gravelly sandy loam, very gravelly loamy sand, very gravelly silt loam, very gravelly loam
GC	Very gravelly clay loam, very gravelly sandy clay loam, very gravelly silty clay loam, very gravelly silty clay, very gravelly clay
SW	Same as SP (except well graded in grain sizes)
SP	Sand, gravelly sand (less than 20 percent very fine sand)
SM	Loamy sand, sandy loam; sand; gravelly loamy sand and gravelly sandy loam
SC	Sandy clay loam, sandy clay; gravelly sandy clay loam and gravelly sandy clay
ML	Silt, silt loam, loam, sandy loam
CL	Silty clay loam, clay loam, sandy clay
OL	Mucky silt loam, mucky loam, mucky silty clay loam, mucky clay loam
MH	Silt, silt loam (highly elastic, micaceous or diatomaceous)
CH	Silty clay, clay
OH	Mucky silty clay
PT	Muck, peat

Note: Modified from Reference 5; see Figure 1 for additional descriptive information.

TABLE 2. USCS SOIL TYPES CORRESPONDING TO USDA SOIL TERMINOLOGY

USDA Soil Type	USCS Soil Type
Gravel, very gravelly loam sand	GP, GW, GM
Sand	SP, SW
Loamy gravel, very gravelly sandy loam, very gravelly loam	GM
Loamy sand, gravelly loamy sand, sand	SM
Gravelly loam, gravelly sandy clay loam	GM, GC
Sandy loam, gravelly sandy loam	SM
Silt loam, sandy clay loam (with fine-grained sand)	ML
Loam, sandy clay loam	ML, SC
Silty clay loam, clay loam	CL
Sandy clay, gravelly clay loam, gravelly clay	SC, GC
Very gravelly clay loam, very gravelly sandy clay loam, very gravelly silty clay loam, very gravelly silty clay	GC
Silty clay, clay	CH
Muck, peat	PT

Note: Modified from Reference 5.

TABLE 3. APPROXIMATE COMPOSITION OF MUNICIPAL SOLID WASTE

Description	Weight Percent
Paper (including cardboard)	40
Garbage	20
Glass/ceramics	10
Grass/dirt	10
Metal	5
Plastic/rubber/leather	5
Wood	5
Plastic film	3
Cloth	2
Total	100

plastic and paper bags, and garbage beginning rapid decomposition. The mixture is very poorly amenable to description in quantitative terms except that it commonly arrives on site at a low unit weight and is changed in one or more of the following steps:

	Unit Weight lb/yd^3
From noncompacting garbage trucks	500
From compactor garbage trucks	600-700
After average compaction on dump[7]	750-850
After extra compaction	1000
Maximum likely on dump (before long-term settlement)	1200

Obviously, the ultimate settlement can be large although 90 percent occurs within 2 to 5 years.[8] In special cases, the waste may be milled or shredded to achieve ultimately densities[9,10] of 1400 to 1600 lb/yd^3 and reduce differential settlement. Baling (after compacting) is another special procedure achieving uniform, high initial density.

Disposal of bulk industrial solid wastes presents engineering problems of a more conventional nature. Solids are usually uniform and fine in texture, and properties can be determined by laboratory testing. The extent of engineering studies will be governed by the pollution potential, with toxic materials receiving high priority. Special effort may be needed for designing retaining dikes, a part of the cover in this manual. Problems with differential settlement of industrial waste with consequent disruption of the cover will not be major ordinarily.

Saturated industrial solid wastes often settle mechanically like consolidating soil, and their behavior is predictable.[11] Likewise, drainage and settlement can be hastened by certain construction techniques. However, some industrial slurries have poor qualities, besides an enduring potential for serious pollution and, by virtue of a colloidal nature, may remain for years in a saturated condition with a very high water content.

SECTION 2

REQUIREMENTS OF COVER ON SOLID WASTE

A common requirement in sanitary landfilling has been that a layer of earth be placed over the compacted solid waste after each day's operation. Most solid waste disposal operations also employ a final, thick soil layer for long-range cover after completion of the operation. A membrane or other synthetic material is sometimes used in place of soil. Intermediate covers are also distinguished for surfaces exposed for long periods but eventually buried by subsequent solid waste lifts. The cover (soil or other material) serves important functions under the general classification of health, aesthetics, and site usage.

COVER FUNCTIONS

The specific functions of cover on solid and hazardous waste sites as determined by the Office of Solid Waste, U. S. Environment Protection Agency (EPA) are outlined below:

a. Health considerations.

  (1) Minimize vector breeding areas and animal attraction by controlling:

    (a) Fly and other insect emergence and entrance.

    (b) Rodent burrowing for food and harborage.

    (c) Bird and animal attractiveness.

  (2) Control water movement to:

    (a) Minimize moisture infiltration, or

    (b) Maximize moisture infiltration.

    (c) Minimize final cover erosion.

  (3) Control potentially harmful gas movement by:

    (a) Minimizing gas movement, or

    (b) Maximizing gas movement.

    - (4) Minimize fire hazard potential by:
        - (a) Controlling movement of atmospheric oxygen.
        - (b) Providing barrier cell walls.
- b. Aesthetic considerations.
    - (1) Minimize blowing paper.
    - (2) Control noxious odors.
    - (3) Provide sightly appearance to the landfill operation.
- c. Site usage considerations.
    - (1) Minimize settlement and maximize compaction to:
        - (a) Assist vehicle support and movement.
        - (b) Insure equipment workability under all weather conditions.
        - (c) Provide for future construction.
    - (2) Provide for vegetative growth.

Several other functions can be added and will logically fall under the heading, "Health considerations" or "Site usage considerations," as follows:

- a. Minimize wind erosion and dust generation.
- b. Resist cold climate deterioration and operational difficulties.
- c. Preserve slope stability.
- d. Resist cracking.
- e. Dewater solid waste.

Within the complete list, a few functions stand out as primary, while the others are usually secondary. Primary functions are more or less independent of others and concern such landfill processes as movement of water and gas and susceptibility to erosion. Secondary functions are considered here to restate primary functions but viewed in a different sense. An example of a secondary cover function is fire resistance; resistance to fire is contingent upon satisfactorily impeding air or gas migration, a primary function. Similarly, slope drainage (and side slope stability) is a secondary or somewhat different way of looking at the primary function, assisting water percolation (infiltration).

The physical characteristics of the cover that are basic to the primary cover functions and are also involved in most of the secondary functions are the conductivity to water, conductivity to gas, shear strength, and tensile strength (or capillary potential).

FUNCTIONAL PRIORITIES

The functions as listed above are straightforward, but in actuality cover functions are complexly interrelated; for this reason, it should be understood that designing solid waste cover involves considerable subjective judgment. A ranking of priorities is necessary in arriving at a determination of which functions are most important at the specific site and in designing features to compensate for adverse side effects on other cover functions. For example, a cover that functions to impede infiltration and percolation of water from the surface will also impede upward movement of decomposition gases. If gases are to be moved through the cover to minimize lateral movement, a gas vent system may be required. A brief hypothetical scenario illustrates the problem of conflicting functions and suggests the priorities approach recommended here.

Suppose that it has been determined that cover for a disposal area receiving hazardous chemical wastes must not only serve all of the usual functions but have special effectiveness in preventing the generation of dust in a region prone to high wind velocity. Suppose that the powdery waste is damp upon arrival at the area but that it dries quickly in the semiarid climate. Finally, suppose that the area is usually subjected to a two-month rainy season in which much of the 15-in. annual precipitation is concentrated.

First priorities for most of the year would be wind erosion resistance and dust control with water infiltration control and other functions following in progressively lower rankings; this is assuming that there are no other particular hazards such as flammability or generation of toxic gas. Control of animals and aesthetic considerations usually fall low in the ranking because they are insensitive to particulars on the choice of soil type. The problem of air pollution by toxic dust particles is solved by specifying that the daily cover shall consist of sand, which by its coarse grain size will resist wind erosion and shall be at least 12 in. in thickness, extra thickness assuring complete shielding of an irregular surface of waste. The infiltration of rainwater largely takes place in the short rainy season; therefore, specifications should require that all intermediate cover exposed during the rainy period shall include, if practical, a 6-in. layer of compacted clay below 6 in. of sand. Finally, it may be specified that certain dust palliatives or water be applied during disposal operations to prevent drying and dust generation by traffic erosion.

SATISFYING REQUIREMENTS AND USING THIS MANUAL

This manual (Figure 5) provides guidance on satisfying the functional requirements of cover on solid/hazardous waste. In Section 4, the general procedure for selecting soil for cover is presented with heavy reliance on a summary tabulation of soil ratings for the various functions. Section 5 reviews all aspects of placement and treatment of cover soil. Section 6 provides information on nonsoil cover materials available for special conditions or especially stringent requirements (particularly to impede water or gas

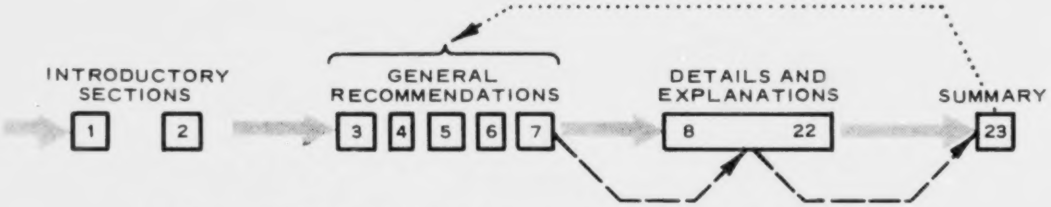


Figure 5. Manual section organization and use.

movement). Section 7 summarizes the overall plan for developing a solid waste cover system.

Sections 8-22 (Figure 5) present the details of each cover function, review pertinent characteristics of soils and other materials, and propose specific design methods taken from the present state of the art of waste disposal or adapted from general soils construction. It may be necessary to consult the appropriate section, 8-22, for clarification of generalizations and terminology used in Sections 4 and 7. This introduction of the summary and recommended methods before the exposition and details is considered to be the more effective organization of the manual. Alternately, it is equally appropriate to consider details function by function before Sections 3-7. In this way, the reader becomes familiar with the important characteristics of soil before they are used for ranking cover effectiveness.

A third way in which this manual can be used is to improve or make more specific the covering procedures already in practice. In this instance, the user will likely find Sections 3-7 to constitute a useful summary, but he may then proceed (Figure 5) to the section or sections dealing with his specific cover problems. Specific needs may be precipitated by economic considerations. For instance, it may be that the soil type usually required by local regulations is not available except at great expense; therefore, assistance is needed in determining an adequate substitute, e.g., in assuring that noxious or flammable gases are controlled until the landfill is stabilized. In such a case, the reader would find guidance on substitute soils and design features in Sections 9 and 17 and on other covers in Section 6.

SECTION 3

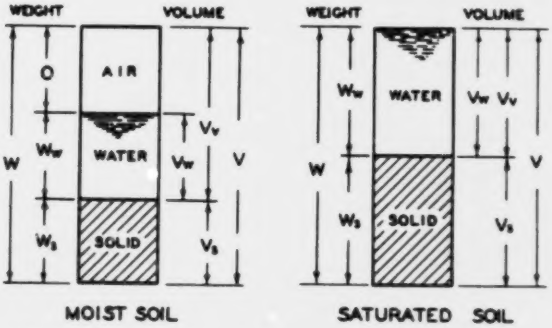
SOIL PROPERTIES AND TESTING

This section summarizes concepts and testing procedures of soil mechanics and geology sufficiently to understand and describe the use of soil for covering solid waste. Much of the presentation has been adapted from Reference 12, but numerous other references on soil mechanics also provide the detailed information for close study. Designations prefixed ASTM refer to standard procedures of the American Society for Testing and Materials to which the reader may also refer; ASTM and Reference 12 procedures are not necessarily identical.

Information is applicable to disturbed or undisturbed natural soil in the foundation or in the borrow area and to soil in place as cover on solid waste. As in all soil engineering, it is important that the designer have his objective clearly in mind when he assigns specific tests, e.g., for general indexing or for water content as placed in cover, etc.

GENERAL RELATIONS

A soil mass is considered to consist of solid particles between which are voids of various sizes, which are filled with gas (air) and water. The fundamental relations of weights and volumes of the components of a soil mass can be derived using the schematic sketches shown in Figure 6. Some of the more important relations used in soil engineering calculations are unit weights (densities), void ratio, porosity, and degree of saturation. The quantities



NOTE: UNIT WEIGHT OF WATER, $\gamma_w = 62.4$ LB/FT.

WATER CONTENT $w = \frac{W_w}{W_s}$

$\theta = \frac{V_w}{V}$

DRY UNIT WEIGHT (DRY DENSITY) $\gamma d = \frac{W_s}{V}$

VOID RATIO $e = \frac{V_v}{V_s}$

POROSITY $n = \frac{V_v}{V} = \frac{e}{1 + e}$

DEGREE OF SATURATION $S = \frac{V_w}{V_v}$

Figure 6. Fundamental relations in soil.

that must be known to compute these relations are the weight and volume of the wet specimen, the weight of the same specimen after oven-drying, and the specific gravity of the solids.[12] The weights of the specimens usually can be obtained without difficulty. The volume of the wet specimen is determined by linear measurement (volumetric method), or by measurement of the volume or weight of water displaced by the specimen (displacement method). See Reference 12 for laboratory procedures. ASTM D 854 prescribes a method for determining specific gravity. Definitions are as follows (also see Figure 6):

a. Dry unit weight γ_d or dry density is the weight of oven-dried soil solids per unit of total volume of soil mass and is usually expressed in pounds per cubic foot.

b. Wet unit weight γ_m or wet density is the weight (solids plus water) per unit of total volume of soil mass, irrespective of the degree of saturation (see below). The wet unit weight is usually expressed in pounds per cubic foot.

c. Void ratio e is the ratio of the volume of voids to the volume of solid particles in a given soil mass.

d. Porosity n is the ratio (usually expressed as a percentage) of the volume of voids of a given soil mass to the total volume of the soil mass.

e. Degree of saturation S is the ratio (usually expressed as a percentage) of the volume of water in a given soil mass to the total volume of voids.

An important component of soil is its water content, which in soil mechanics is designated w and defined as the ratio (usually expressed as a percentage) of the weight of water in a given soil mass to the weight of solid particles. Water content is also quantified as Θ the ratio of volume of water to the total volume of the given soil mass; in fact this definition is preferred in some fields other than soil mechanics. Water content is routinely determined in the laboratory by weighing the soil specimen before and after drying in an oven to constant weight at 110 ± 5°C (ASTM D 2216) Relations in Figure 6 indicate that volumetric water content may be expressed as

$$\Theta = nS \tag{1}$$

Other relationships among the measured quantities[13] allow Equation 1 to be extended to the following useful expression in the nonpercentage form

$$\Theta = \frac{w\gamma_m}{(1 - w)\gamma_w} \tag{2}$$

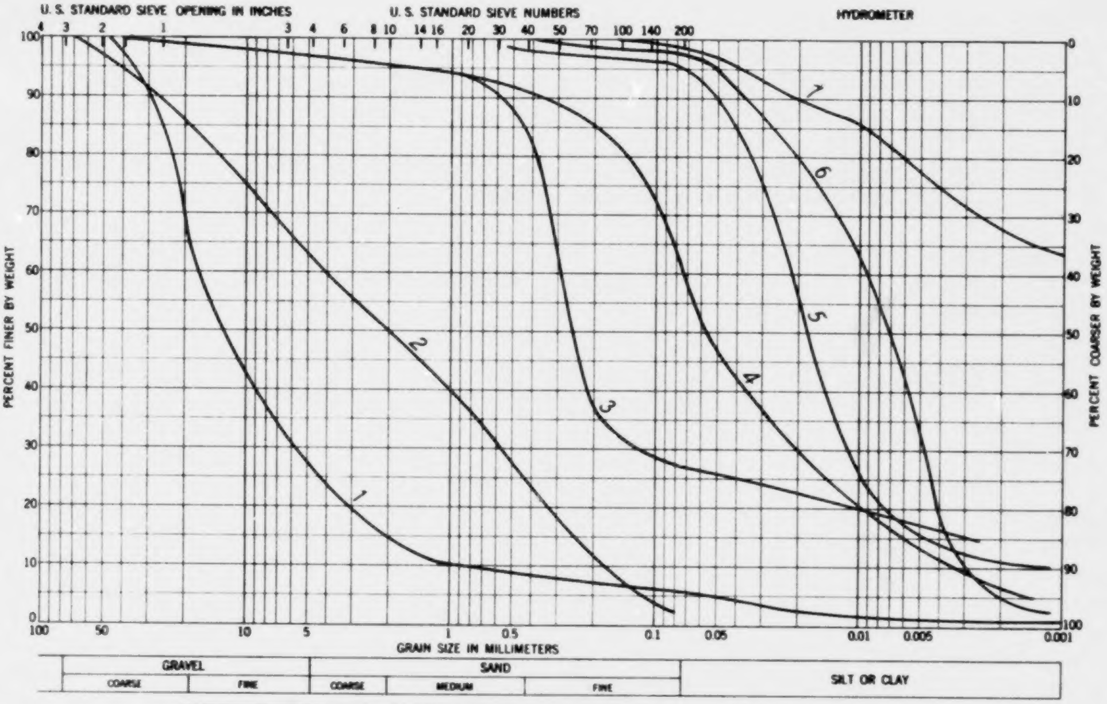
where γ_w is unit weight of water.

GRAIN-SIZE ANALYSIS

Grain-size analysis is a process in which the proportion of each grain size present in a given soil (grain-size distribution) is determined. Figure 7 displays in the usual way the distributions of grain sizes for seven representative soils . Grain-size distribution of coarse-grained soils is determined directly by sieve analysis, while that of fine-grained soils is determined indirectly by hydrometer analysis. Sieve and hydrometer analyses (ASTM D 422) are used in combination for mixed soils.

Sieve Analysis

A sieve analysis consists of passing a dried sample through a set of sieves and weighing the amount of material retained on each sieve. Sieves are



SAMPLE NO.	ELEVATION OR DEPTH	CLASSIFICATION	NAT W%	LL	PL	PI
1	MISSION CANYON, CALIFORNIA	SANDY GRAVEL (GP)	10.8	NON-PLASTIC		
2	TACOMA, WA	GRAVELLY SAND (SW)	3.0	NON-PLASTIC		
3	HAZLEHURST, MS	CLAYEY SAND (SC)	12.0	21.0	12.0	9.0
4	CENTRALIA, WA	SANDY SILTY CLAY (CL)	30.5	40.0	21.0	19.0
5	VICKSBURG, MS	SILT (ML)	18.0	30.0	26.0	4.0
6	KENT HIGHLANDS, WASHINGTON	CLAYEY SILT (ML)	27.3	33.1	24.7	8.4
7	DALLAS, TEXAS (WALNUT HILLS)	FAT CLAY (CH)	34.9	68.0	27.0	41.0

Figure 7. Gradation curves of some sanitary landfill cover soils (from Reference 5 and this study)

constructed of wire screens with square openings of standard sizes. The sieve analysis is performed on material retained on a U. S. Standard No. 200 sieve. The sieve analysis, in itself, is applicable to soils containing a small portion passing the No. 200 sieve provided the grain-size distribution of that portion is not of interest. The percentage of material by weight retained on the various sieves is computed as follows:

$$\text{Percent retained} = \frac{\text{weight retained on a sieve}}{\text{total weight of oven-dried sample}} \times 100$$

Hydrometer Analysis

The hydrometer method of analysis is based on Stokes' law, which relates the terminal velocity of a sphere falling freely through a fluid to the diameter. It is assumed that Stokes' law can be applied to a mass of dispersed soil particles of various shapes and sizes. The hydrometer is used to determine the percentage of dispersed soil particles remaining in suspension at a given time. The maximum grain size equivalent to a spherical particle is computed for each hydrometer reading using Stokes' law. The hydrometer analysis is applicable to soils passing the No. 10 sieve for routine classification purposes; when greater accuracy is required (such as in the study of frost-susceptible soils), the hydrometer analysis should be performed on only the fraction passing the No. 200 sieve.

ENGINEERING INDICES

The Atterberg limits are standardized index water contents used to define the various states of consistency for fine-grained soils. Important states from a geotechnical standpoint are shown in Figure 8. For testing procedures, see Reference 12 or ASTM D 423 and D 424.

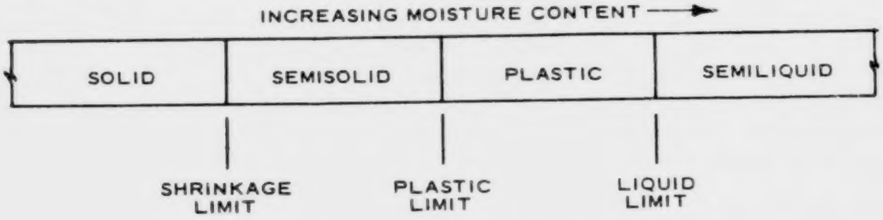


Figure 8. States of consistency of soil.

Liquid Limit

The liquid limit (LL) of a soil is the water content, expressed as a percentage of the weight of oven-dried soil, at which two halves of a soil pat separated by a groove of standard dimensions will close at the bottom of the groove along a distance of 1/2 in. under the impact of 25 blows in a standard LL device. The LL represents the boundary between plastic and semiliquid conditions.

The LL device holds the soil pat in a brass cup, which is raised and then dropped (10 mm) by a crank and cam onto a block of resilient material. The cam must be shaped so that the height of the cup is maintained constant for a short section at the end of the turn rather than rising continuously to the point of release. The LL is determined from four tests at different water contents by plotting water content versus number of blows to closure (semilogarithmic). The intersection of a straight line through the test points and the 25-blow line on the graph gives the LL.

Plastic Limit

The plastic limit (PL) of a soil is the water content, expressed as a percentage of the weight of oven-dried soil, at which the soil begins to crumble when rolled into a thread 1/8 in. in diameter. The PL represents the boundary between plastic and semisolid conditions.

In the test procedure take 2 to 5 gm of the same material used for the LL test at any stage of drying at which the mass becomes plastic enough to be shaped without sticking. Shape into an ellipsoidal mass and roll into a thread carefully. When the diameter of the thread becomes 1/8 in. without crumbling, fold and knead the thread into a ball again and repeat the rolling process. When this process has dried the soil to the point where the thread will break into numerous pieces having a diameter of 1/8 in. and about 1/8- to 3/8-in. length, determine the w to obtain PL.

Plasticity Index

The difference between LL and PL is the plasticity index (PI). The PI indicates the range of plasticity of the given soil, and generally, the higher the PI, the greater the plasticity.

Shrinkage Limit

The shrinkage limit (SL) of a soil (remolded) is the water content, expressed as a percentage of the weight of the oven-dried soil, at which further loss in moisture will not cause a decrease in its volume. In determining SL, accurate measurements of volume are critical. Reference 12 describes the recommended mercury displacement technique. The SL represents the boundary between semisolid and solid conditions.

AGRICULTURAL INDICES

Soil chemistry and water storage are important considerations in planning for support of vegetation.

Water Storage

The availability states of water in soil have fundamental importance in agriculture, and an understanding of the concept is helpful in selecting and designing solid waste cover. One can distinguish bound water, available water, and gravitational water for a given soil according to availability for use by plants (Figure 9). Boundaries of these simplistic states of water are defined by two quantities that can be determined using apparatus for measuring soil suction pressure (negative or tension pore pressure), but such tests are

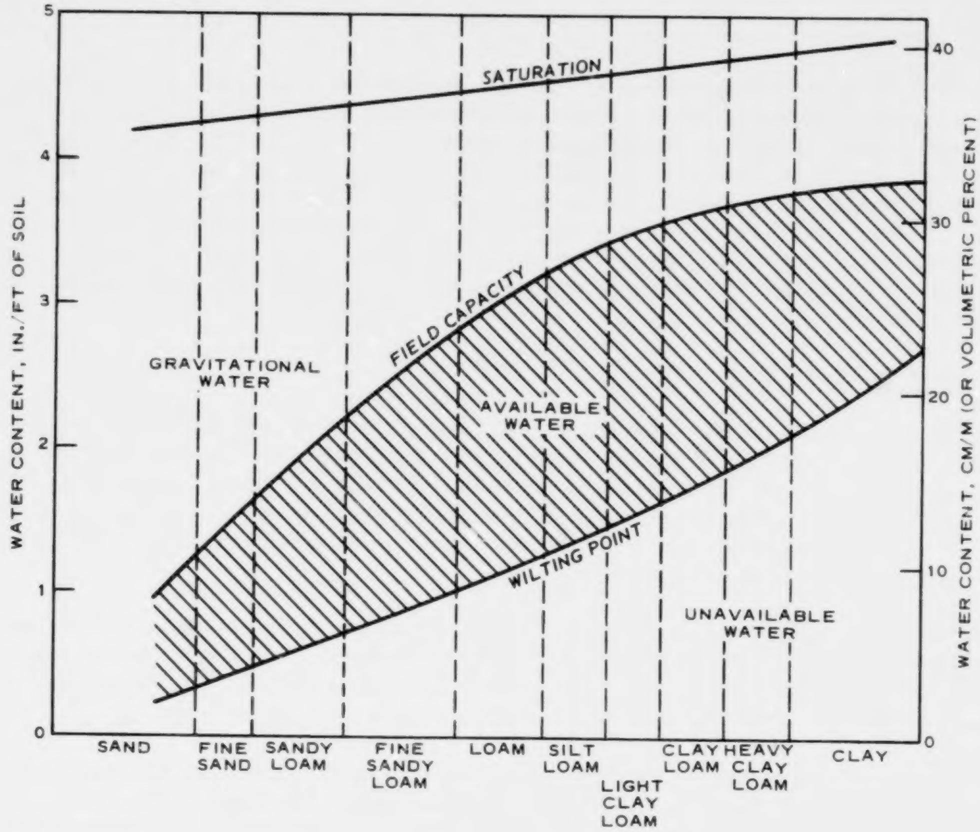


Figure 9. Water-holding characteristics of USDA soils.

not undertaken ordinarily for cover design. Actually, the conditions will probably change as vegetation becomes established. Estimations based on soil type are used instead (Figure 9).

Field capacity. Field capacity is the maximum water content retained in soil without draining by gravity, i.e., the storage capacity for capillary water. In order to standardize this somewhat arbitrary point, agronomists use the soil suction pressure of 0.33 atmospheres.

Wilting point. Wilting point is the lower limit of plant utilization of capillary water. The soil suction pressure at this point is 15 atmospheres by definition.

Soil Chemistry

A review of soil characteristics that are important to the support of vegetation is given under SOIL FACTORS in Section 19. These characteristics mainly concern soil chemistry and particularly the contents of nutrients and the pH of pore water.

COMPACTION TESTS

The laboratory compaction procedure is intended to simulate the compactive effort anticipated in field construction. A standard, 25-blow compaction test (also called the standard Proctor test) is used to simulate field compaction for most routine foundation and embankment design. To simulate solid waste cover placement, it is appropriate to use lower compactive efforts. Five- and fifteen-blow compaction tests are recommended here for municipal solid waste. Compaction tests are made on a soil at various water contents to establish a relation between water content and unit weight of the compacted soil.

Standard (25-Blow) Compaction

The standard method apparatus consists of a cylindrical metal mold (Figure 10), with detachable collar approximately 2-1/2 in. high, that can be fastened firmly to a detachable baseplate. A 4-in.-diam mold is used for compacting samples composed entirely of material passing a No. 4 sieve. A 6-in. mold is used for compacting samples containing material retained on the No. 4 sieve and passing the 3/4-in. sieve.

The metal hand rammer (Figure 10) is of the sliding-weight, fixed-head type having a 2.0 ± 0.005-in.-diam circular face and a free-falling weight of 5.5 ± 0.02 lb. The rammer is equipped with a guide for controlling the height of fall of the sliding weight to the prescribed 12.0 ± 0.06 in.

Sufficient amounts of the prepared sample are placed in the 4-in. mold in three equal layers to give a total compacted depth of approximately 5 in. Each layer is compacted by 25 uniformly distributed blows from the rammer; the energy input during compaction is given in Table 4 in comparison to other tests. The standard procedure for soils containing material retained on the No. 4 sieve is the same except that the diameter of the test mold is 6 in. and

TABLE 4. TEST COMPACTION ENERGY

Compaction Test	Approximate Equivalent* ASTM	AASHTO	Compaction Input ft-lb/ft^3
Standard	D 698	T-99	12,375
15-blow	-	-	7,425
5-blow	-	-	2,475
Modified†	D 1557	T-180	56,750

* Other approximately equivalent procedures for standard and modified compaction tests.

† Not recommended for most solid waste cover testing.

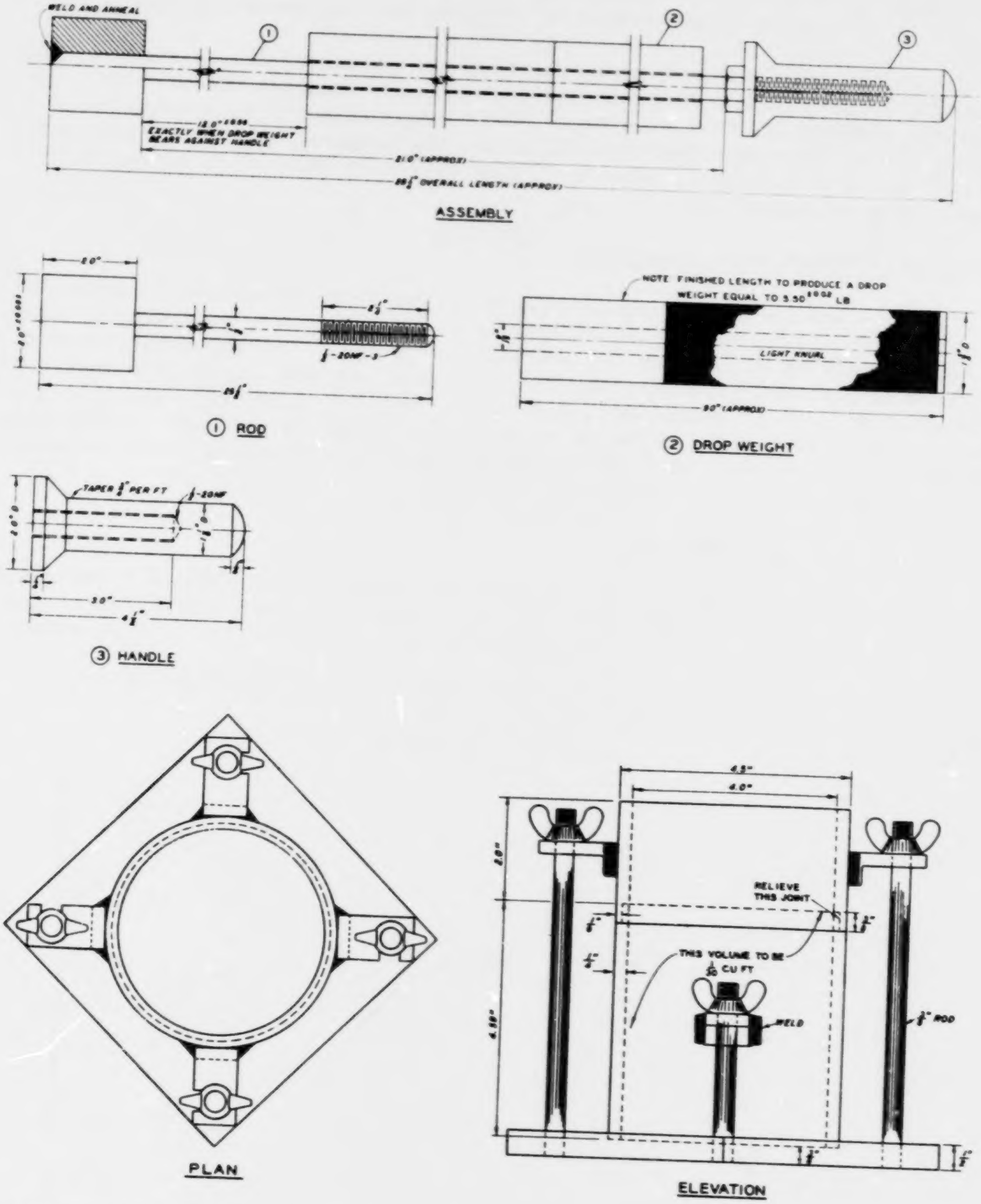

WELD AND ANNEAL
①
②
③
12.0" ±0.06
EXACTLY WHEN DROP WEIGHT BEARS AGAINST HANDLE
21.0" (APPROX)
OVERALL LENGTH (APPROX)
ASSEMBLY
2.0"
NOTE FINISHED LENGTH TO PRODUCE A DROP WEIGHT EQUAL TO 5.50 ±0.02 LB
LIGHT KNURL
20" (APPROX)
① ROD
② DROP WEIGHT
TAPER PER FT
-20NF
3.0"
③ HANDLE
PLAN
4.5"
4.0"
2.0"
4.59"
RELIEVE THIS JOINT
THIS VOLUME TO BE 1/30 CU FT
WELD
ROD
ELEVATION

Figure 10. Typical 4-in.-diam compaction mold and sliding-weight, fixed-head rammer for standard compaction test.12

the number of blows of the compaction rammer is 56 per soil layer instead of 25. This results in equal compactive efforts for the two molds (Table 4).

A sufficient number of test specimens are compacted over a range of water contents to establish definitely the optimum water content and maximum density. Generally, five specimens should completely define a compaction curve. It is sometimes important to store the prepared soil in an airtight container for a sufficient length of time to permit absorption of moisture (also refer to ASTM D 698).

Five- and Fifteen-Blow Compaction

The 5- and 15-blow compaction tests differ from the standard compaction test in that lesser compactive efforts are used (Table 4), resulting in lower maximum densities and higher optimum water contents. The apparatus, preparation of sample, and procedure are the same as those used in the standard compaction test (5.5-lb weight with a 12.0-in. free drop), except that only the 4-in. mold is used and the number of blows per layer is reduced. These tests appear to give results more like those achieved in compacting cover on municipal solid waste (see Section 5).

Presentation of Test Results

The results of compaction tests are presented in the form of a compaction curve on a plot of dry densities (dry unit weights) versus the corresponding water contents (Figure 11). The plotted points are connected with a smooth

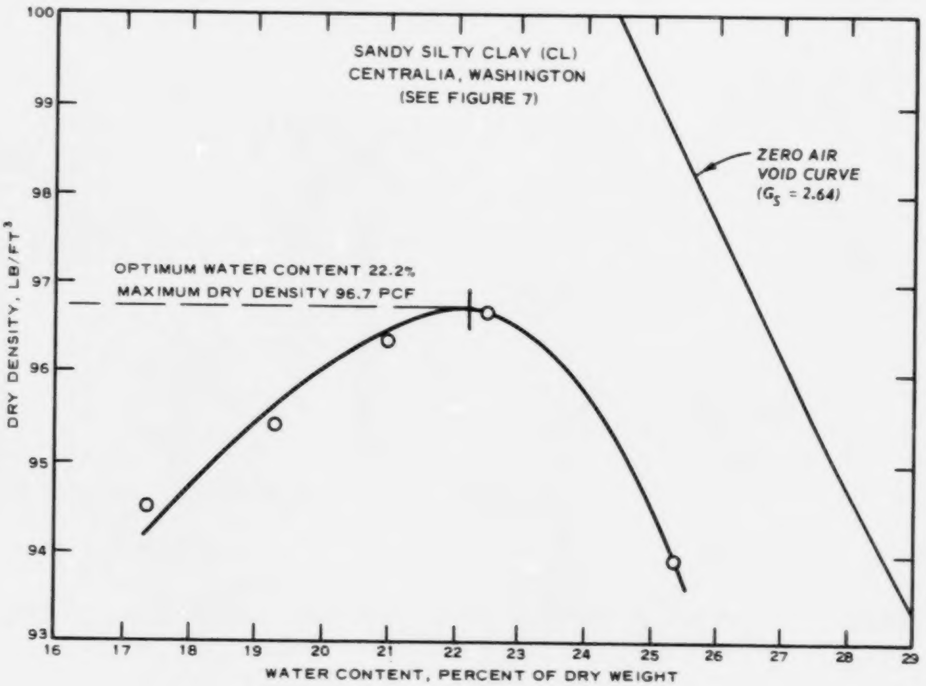


Figure 11. Standard compaction test results with landfill cover soil.

curve; for most soils, the curve approaches a parabolic form. The water content at the peak of the compaction curve is designated the optimum water content. The dry density of the soil at the optimum water content is the maximum dry density. The zero air void curve (Figure 11) represents the dry density and water content of the soil completely saturated with water. The curve of zero air voids should be shown with the compaction curve.

Relative Density

The degree of compactness of a cohesionless (granular) soil is sometimes expressed in simplified, different terms as percent relative density. The lower limit corresponding to 0 percent relative density is obtained by pouring the soil loosely into the container. The upper limit at 100 percent relative density is reached by tamping and shaking down to a minimum volume. Refer to ASTM D 2049 for procedures.

PERMEABILITY TESTS

The flow of water through saturated soil is assumed to follow Darcy's law for laminar flow:

$$q = kiA \tag{3}$$

where q = rate of discharge through a soil of cross-sectional area A at 20°C
k = coefficient of permeability (also called hydraulic conductivity)
i = hydraulic gradient: the loss of hydraulic head per unit distance of flow

The application of Darcy's law to a specimen of soil in the laboratory is illustrated in Figure 12. The k has the dimensions of a velocity and is usually expressed in centimeters per second. Permeability depends primarily on the size and shape of the soil grains, the void ratio of the soil (compaction), the shape and arrangement of the voids, and the degree of saturation. See Section 8 regarding complications introduced by unsaturated conditions.

Constant-head Test

The simplest method for determining k is the constant-head type of test illustrated in Figure 12. This test is performed by measuring the quantity of water Q and the elapsed time t. The head of water is kept constant throughout the test. For fine-grained soils, Q is small and may be difficult to measure accurately. Therefore, the constant-head test is used principally for coarse-grained soils (clean sands and gravels) with k values greater than about 10^{-3} cm/sec.

Falling-head Test

The principle of the falling-head test is illustrated in Figure 13. This test is conducted in the same manner as the constant-head test, except that the head of water is not maintained constant but is permitted to fall within the upper part of the specimen container or in a standpipe directly connected to the specimen. The quantity of water flowing through the specimen is

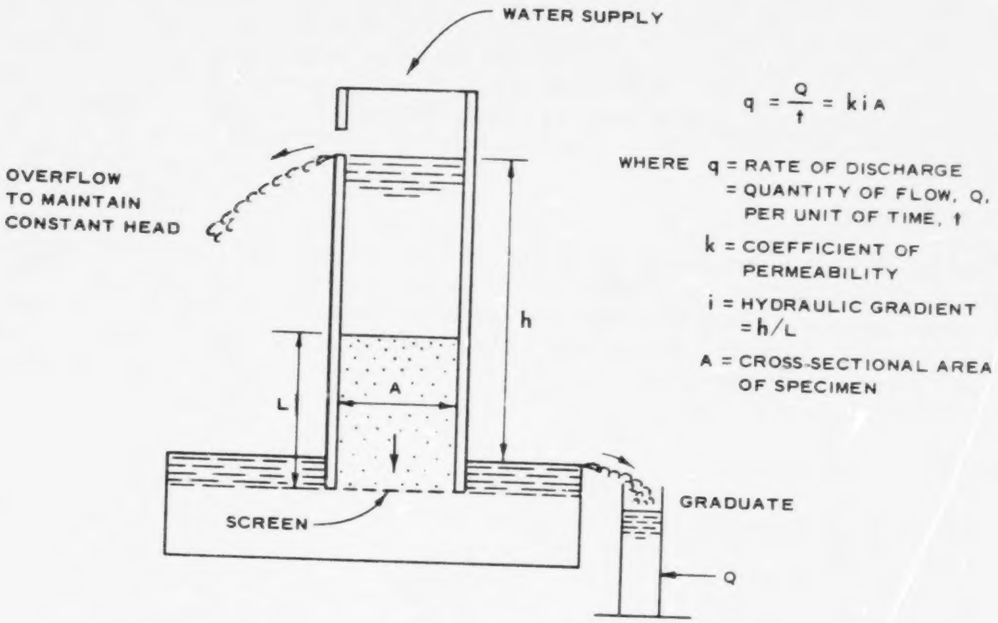

WATER SUPPLY
OVERFLOW TO MAINTAIN CONSTANT HEAD
h
L
A
SCREEN
GRADUATE
Q
q = Q/t = k i A
WHERE q = RATE OF DISCHARGE
= QUANTITY OF FLOW, Q, PER UNIT OF TIME, t
k = COEFFICIENT OF PERMEABILITY
i = HYDRAULIC GRADIENT = h/L
A = CROSS-SECTIONAL AREA OF SPECIMEN

Figure 12. Flow of water through saturated soil.[12]

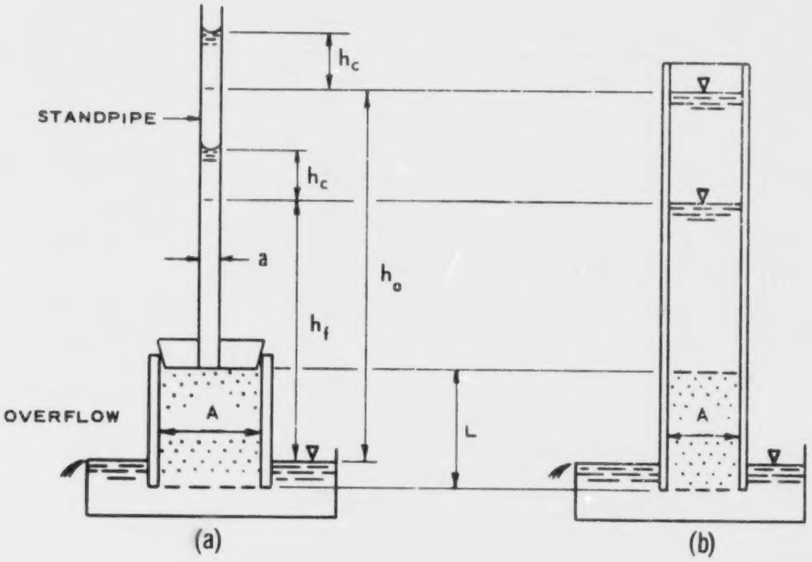
determined indirectly by computation. The falling-head test is generally used for less pervious soils (fine sands to clays) with k values less than 10^{-3} cm/sec.

Estimating k

Reliable determination of k in the laboratory requires facilities and experience not ordinarily expected in organizations charged with designing cover. Accordingly, the value of k may be estimated. Table 5 provides useful estimates, but some caution should be exercised here since soil structure and compaction have major effects on k . Generally, agricultural top soils preserving vestiges of natural aggregate structure and root holes are much more permeable than freshly reworked or compacted subsoils. By the same token, some allowance may have to be made for increasing permeability with time as the cover soil becomes naturalized with vegetation and sod.

STRENGTH TESTS

Site-specific strength data are usually not needed for designing cover; therefore, the following tests for determining strength under various conditions are not often assigned. Important exceptions are in cases where cover soil is to provide support to the sloping side of the disposal area (see Section 13). Testing may be even more important in evaluating the strength of the foundation of such retaining covers or dikes. The value of simple strength indices is shown for predicting operational trafficability in Section 14.



USING SETUP SHOWN IN (a), THE COEFFICIENT OF PERMEABILITY IS DETERMINED AS FOLLOWS:

$$k = \frac{La}{At} \ln \frac{h_o}{h_f} = 2.303 \frac{La}{At} \log_{10} \frac{h_o}{h_f}$$

USING SETUP SHOWN IN (b), THE COEFFICIENT OF PERMEABILITY IS DETERMINED AS FOLLOWS:

$$k = \frac{L}{t} \ln \frac{h_o}{h_f} = 2.303 \frac{L}{t} \log_{10} \frac{h_o}{h_f}$$

WHERE: h_c = HEIGHT OF CAPILLARY RISE
a = INSIDE AREA OF STANDPIPE
A = CROSS-SECTIONAL AREA OF SPECIMEN
L = LENGTH OF SPECIMEN
h_o = HEIGHT OF WATER IN STANDPIPE ABOVE DISCHARGE LEVEL MINUS h_c AT TIME, t_o
h_f = HEIGHT OF WATER IN STANDPIPE ABOVE DISCHARGE LEVEL MINUS h_c AT TIME, t_f
t = ELAPSED TIME, $t_f - t_o$

Figure 13. Principle of falling-head test.[12]

TABLE 5. APPROXIMATE AVERAGE PERMEABILITY* AND CAPILLARY HEAD OF SOILS

General Soil Type	USCS Soil Type	Coefficient of Permeability, cm/s	Capillary Head, cm
Gravel	GP	10^{-1}	---
	GW	10^{-2}	6
	GM	5×10^{-4}	68
	GC	10^{-4}	---
Sand	SP	5×10^{-2}	---
	SW	10^{-3}	60
	SM	10^{-3}	112
	SC	2×10^{-4}	---
Silt	ML	10^{-5}	180
	MH	10^{-7}	---
Clay	CL	3×10^{-8}	180
	CH	10^{-9}	200 - 400+

* See effect of compaction in Section 5.

The shear strength of soil is considered to obey the Mohr-Coulomb criterion

$$S = c + \sigma \tan \phi \tag{4}$$

where c = cohesion
σ = normal stress on the shear surface, and
ϕ = angle of internal friction (Figure 14)

By definition, $c = 0$ for cohesionless soils, such as sand, and intrinsic strength is entirely reflected in ϕ. With the pore water pressure u taken into consideration, the criterion becomes

$$S = c' + (\sigma - u) \tan \phi' \tag{5}$$

where c' and ϕ' are comparable to c and ϕ except for being under effective stress conditions.

Cone Index and Remolding Index

Relative shear strength of an undisturbed, fine-grained soil can be evaluated with a cone penetrometer. This instrument employs a 30-deg cone with 1/2-in.^{2} base-end area. The force necessary to push the cone slowly through the soil is indicated by a dial that ranges from 0 to 300. The value 300 occurs under a force of 150 lb. The measured value, termed cone index

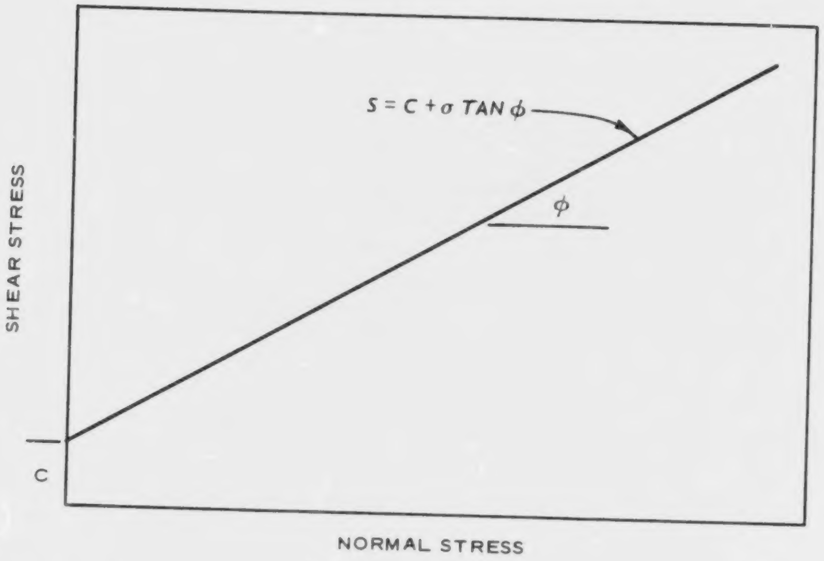


Figure 14. Graphical criterion of shear strength of soil.

(CI), is useful as a dimensionless index of strength.

As traffic and other loads act on moist or wet soil, the soil is remolded further and its strength usually is changed. Remolding index (RI) procedures, one for fine-grained soils and another for poorly drained, coarse-grained soils with fines, have been devised to quantify this strength change.[6] For fine-grained soils, an undisturbed sample is taken with a sampler and extruded into a cylinder mounted on a base. The CI values for the undisturbed soil are read at the surface and at 1-in. increments to a depth of 4 in. with the cone penetrometer. One hundred blows of a 2.5-lb hammer, dropped 12 in., are then applied, and CI values are obtained in the remolded soil. The RI is determined by dividing the sum of the five CI readings made after remolding by the sum of the five readings made before remolding. Coarse-grained soils with fines are indexed similarly except a different cone size and remolding procedure are used.

Drained Direct Shear

The direct shear test is used commonly to measure the shear strength of fine-grained soil[14] under drained (effective stress) conditions. A relatively thin, square block of soil is placed in a rigid box (Figure 15) that is divided horizontally into two frames, the block is confined under a vertical (normal) stress, and a horizontal force is applied so as to fail the block along a horizontal plane at its midheight. Generally, a minimum of three specimens, each under a different normal stress, are tested to establish the relation (Figure 14) between shear strength and normal stress in terms of effective cohesion c' and effective friction angle ϕ'. The magnitudes of the normal stresses used depend on the range of stresses anticipated for design. Because of the difficulties involved in controlling soil drainage during direct shear, only the S-test procedure[12] in which complete consolidation

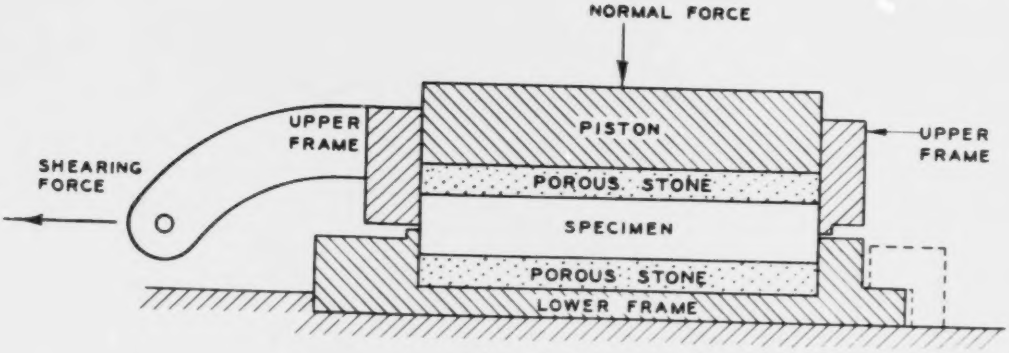

NORMAL FORCE
UPPER FRAME
PISTON
UPPER FRAME
SHEARING FORCE
POROUS STONE
SPECIMEN
POROUS STONE
LOWER FRAME

Figure 15. Schematic diagram of direct shear box.[12]

is permitted under each increment of normal and shear stress is recommended.

Triaxial Compression

In the triaxial compression test, a cylindrical specimen of soil encased in a rubber membrane is placed in a chamber, subjected to a confining fluid pressure (Figure 16), and then loaded axially to failure.[12] Controlled drainage of pore water may be permitted. Three specimens are usually run under different confining pressures to establish the relation between shear strength and normal stress. Prior to shear, the three principal stresses are equal to

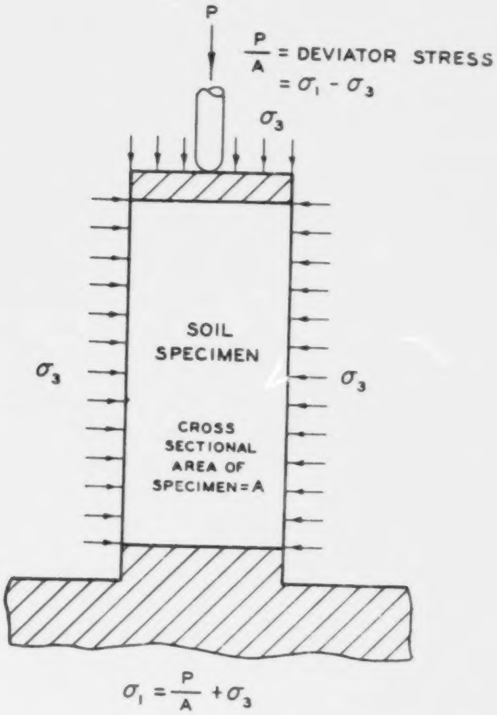

P
$\frac{P}{A}$ = DEVIATOR STRESS
$= \sigma_1 - \sigma_3$
σ_3
SOIL SPECIMEN
σ_3
σ_3
CROSS SECTIONAL AREA OF SPECIMEN = A
$\sigma_1 = \frac{P}{A} + \sigma_3$

Figure 16. Schematic diagram showing stresses during triaxial compression test.[12]

the chamber fluid pressure. During shear, the major principal stress σ_1 is equal to the applied axial (deviator) stress plus the minor principal stress (chamber pressure) σ_3 (Figure 16).

Three basic triaxial compression test procedures are unconsolidated-undrained, consolidated-undrained, and consolidated-drained, the Q, R, and S tests, respectively. The procedure is selected to simulate closely, or to bracket, the conditions anticipated in the field. In the Q test, the water content of the specimen is not permitted to change during the application of the confining pressure or during the axial loading of the specimen to failure. The Q test usually is not applicable to soils that are free-draining, i.e., to soils having a permeability greater than 10^{-3} cm/sec. In the R test, complete consolidation of the specimen is permitted under the prescribed confining pressure. Then, with the water content held constant (no further consolidation), the specimen is axially loaded to failure. Specimens must as a general rule be completely saturated before application of the deviator stress. The S-test procedure allows complete consolidation of the test specimen under the confining pressure and during the axial loading to failure. Consequently, no excess pore pressure exists at the time of failure. Also see S test under Drained Direct Shear.

CONSOLIDATION TEST

When a saturated soil is loaded, consolidation occurs by a slow drainage of pore water. Consolidation behavior is insignificant in cover soil but can assume importance occasionally in foundations of retaining slopes and embankments and in the solid waste itself (when saturated). Where either material is clayey or otherwise drains especially slowly, pore pressure may rise under the new loading and lead to slope instability or bearing capacity problems (see Equation 5).

The routine test[12] to quantify consolidation behavior consists of incrementally loading a soil specimen in one dimension in a consolidometer (Figure 17) and measuring for each increment the displacement at various elapsed times up to 24 hours. Figure 18 shows a record of one increment of loading. Only the so-called primary consolidation is related to expulsion of water. Free drainage is necessarily permitted, of course (refer to ASTM D 2435).

From each displacement-time plot for all load increments, the total displacement at the end of a selected time interval (commonly 24 hours) is obtained. Next, the displacement data are converted to void ratio changes and related to pressure as in Figure 19. The compression index C_c can then be obtained for direct use in settlement prediction (see Section 15) as indicated in the figure. Where the e-p plot is curved at the pressure of interest instead of linear, C_c is the slope of the tangent.

SWELL TESTS

The shrink/swell behavior of fine, clay-rich soils can be excessive in some regions of the United States, and testing may occasionally be necessary to evaluate the need for special requirements of design or construction.

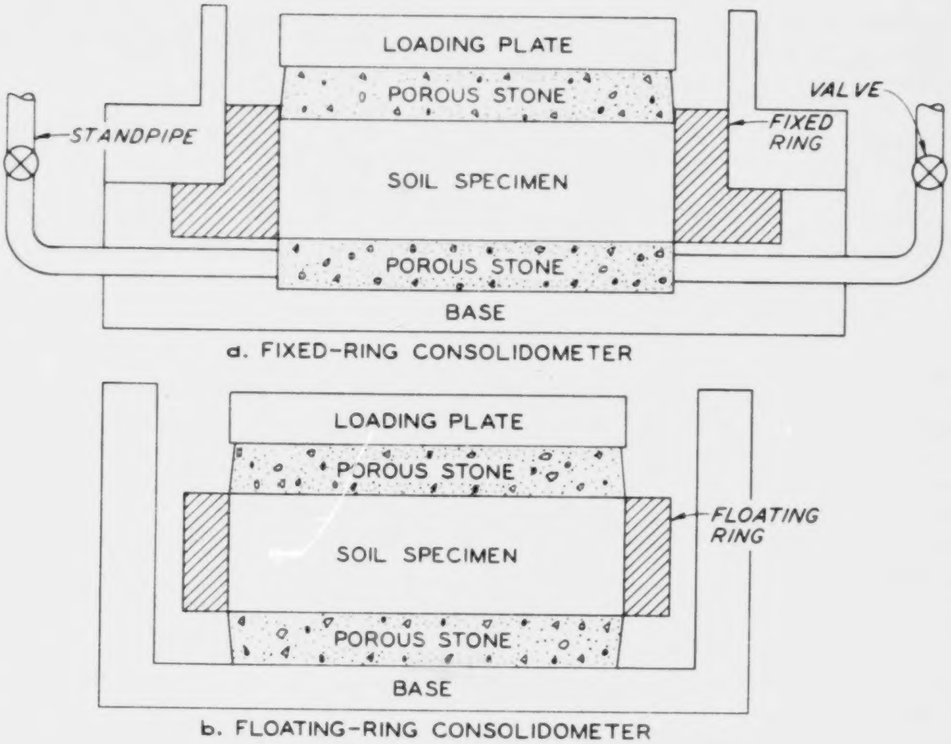

LOADING PLATE
POROUS STONE
STANDPIPE
VALVE
FIXED RING
SOIL SPECIMEN
POROUS STONE
BASE
a. FIXED-RING CONSOLIDOMETER
LOADING PLATE
POROUS STONE
FLOATING RING
SOIL SPECIMEN
POROUS STONE
BASE
b. FLOATING-RING CONSOLIDOMETER

Figure 17. Schematic diagrams of fixed-ring and floating-ring consolidometers.[12]

Engineering indices are usually very useful for predicting such behavior as explained in Section 18.

In rare cases, swell testing may be deemed necessary by the importance or size of the covering operation. The swell test is a simple, routine laboratory test[15] that provides quantitative information on swell pressure or linear swell of the soil. Standard consolidometer and loading bar device[12] are used in one of two modes.

a. Hold the loading bar constant (constant specimen volume) and measure maximum uplift pressure resulting from saturation.

b. Hold the load constant and measure the vertical movement (specimen volume change) resulting from saturation.

Swell tests have provided useful guidance for field compaction of swell-prone soil; however, the essence, as applied to cover soils over solid waste, often lies in the generalizations that have come from previous studies.

SOIL SUCTION TESTS

Soil suction pressure is used in some theoretical analyses of water

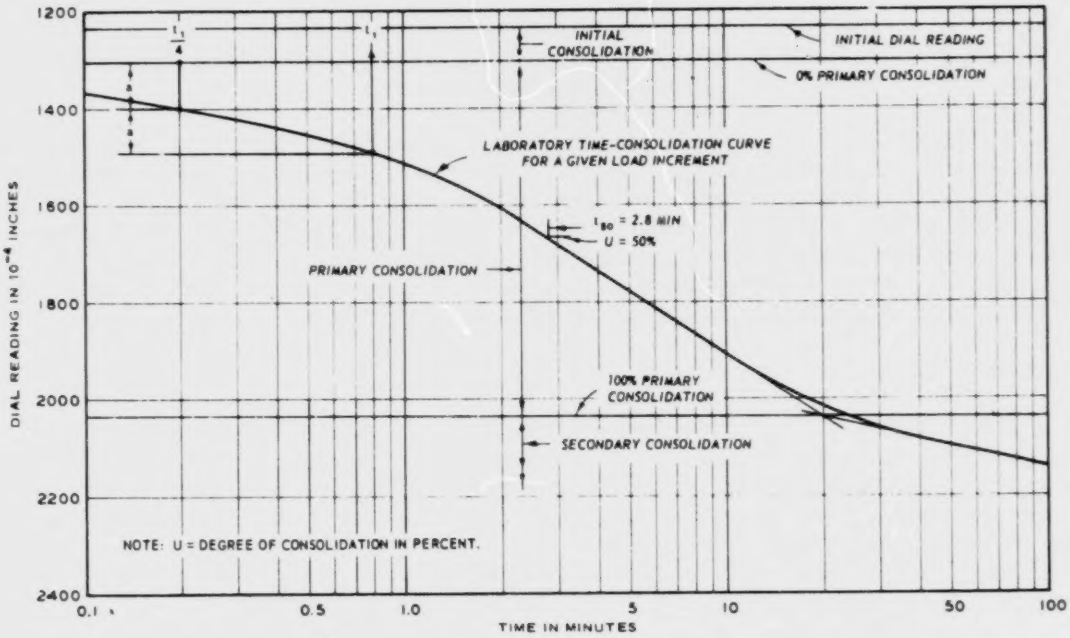


Figure 18. Time-consolidation curve.

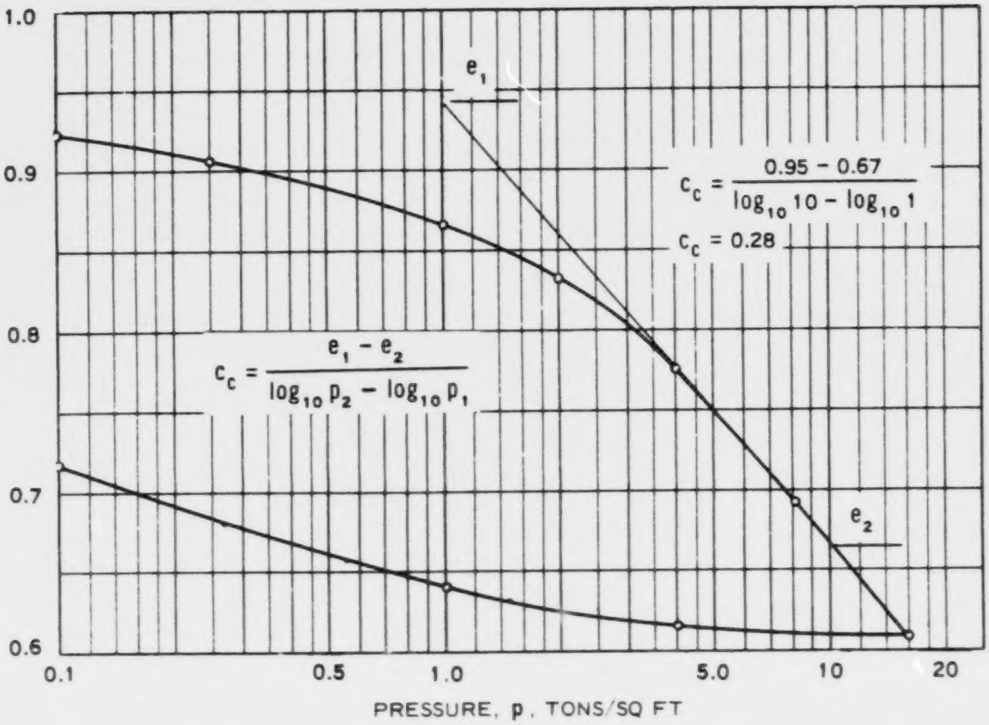


Figure 19. Void ratio-pressure curve.[12]

movement in unsaturated soils. Such analyses are beyond the scope of this manual, and suction pressure is not routinely used in designing cover. Test methods are available but not reviewed here.

Capillary head H_c can be considered a property of the soil determining the tenacity for holding water. Active H_c marks the height above the water table to which water will rise by capillary action in the given soil. Passive H_c is the height above the water table to which capillary water will drain from a transient condition of saturation. Though conceptually simple, H_c is not routinely determined in most geotechnical laboratories. The designer can use estimates of relative capillarity such as in Table 5.

DISPERSION TESTS

Dispersion tests are another special group of tests for characterizing fine-grained soils suspected of having a tendency to erode rapidly. The so-called dispersion and pinhole tests are reviewed in the ASTM volume that includes Reference 16. In almost all cases, the designer should rely on experience of soil conservation specialists and engineers familiar with local conditions rather than attempting a testing program. It should be sufficient to know that a dispersive tendency exists or does not exist.

MINERALOGICAL ANALYSIS

Information on the clay mineralogy of a soil is useful background in site investigations and for designing cover. An X-ray diffraction analysis obtains a semiquantitative estimate of abundances of montmorillonite, illite, kaolinite, etc., in the finest fraction that, in combination with data from a hydrometer grain-size analysis, reveals much of the engineering behavior to be expected. However, clay mineralogy can be immensely complicated by the common occurrence of interlayered combinations of the basic clay minerals. Even within the important montmorillonite group the exchangeable cation position in the mineral structure determines the degree of swelling behavior.

Ordinarily, the consideration of mineralogical aspects of cover at a site should be assigned to a geologically oriented office or laboratory. It will often be found that sufficient mineralogical background already exists and new analyses are unnecessary.

SECTION 4

SELECTION OF SOIL FOR COVER

Details in Sections 8-22 are summarized in the following paragraphs and brought to bear on the task of selecting the most suitable soil for cover. The functions of solid waste cover are considered in Table 6 and the various soil types are ranked according to suitability.

DETERMINATION OF COVER FUNCTIONS

The numerous functions of cover identified in Section 2 and listed in Table 6 must first be ranked by importance. This ranking process is a key part of the selection procedure, but it can only be accomplished site specifically. For example, at many landfills the rate of percolation of surface water may be of utmost importance; elsewhere, for instance in arid regions, this function is entirely subordinate. Long- and short-term functions should be separated and given some absolute ranking. For example, it is difficult to distinguish the relative importance of reduction in dust during the operation of a landfill as opposed to the reduction of potential for fires, where the latter suggests covering and enclosing cells in clay-rich, but dust-prone, soil. These decisions are made at the design stage. Only at this point in the development of the project can the actual conditions, such as climate, soil availability, transportation costs, and population proximity, be evaluated in the context of the generalizations made in this manual.

For each function judged to be significant, soils should be ranked from best to worst. This step has already been accomplished in Table 6. Next, it will be necessary to flag those soils that are actually available for use at the site. These may include materials brought in from a distance to upgrade indigenous soil or soil brought in where indigenous soils are insufficient in quantity. Allowance may be needed for the high cost of importing materials.

EXPLANATION OF SOIL RATING

The rating of soils accomplished in Table 6 is based on the following discussions. Functional ratings of soil are from I (best) to as many as XIII (poorest). Quantitative parameters are also provided wherever available, so that the reader can see the absolute position of a particular soil rating.

The first column in Table 6 concerns the go/no go aspect of trafficability. The ratings of I to XII from coarse granular to fine peaty soils are based on a complete set of rating cone index (RCI) values as discussed in Section 14. In column 2 the stickiness trafficability based on the weight percent of clay is given. A complete set of values for this parameter is

TABLE 6. RANKING OF USCS SOIL TYPES ACCORDING TO PERFORMANCE OF COVER FUNCTIONS

USCS Symbol	Typical Soils	Trafficability			Water Percolation		Gas Migration	
		Go-No Go (RCI Value)*	Stickiness (Clay, %)	Slipperiness (Sand-Gravel, %)	Impede (k, cm/s)*	Assist (k, cm/s)*	Impede (H_c, cm)*	Assist (H_c, cm)*
GW	Well-graded gravels, gravel-sand mixtures, little or no fines	I (>200)	I (0-5)	I (95-100)	X (10^{-2})	III	X (6)	I
GP	Poorly graded gravels, gravel-sand mixtures, little or no fines	I (>200)	I (0-5)	I (95-100)	XII (10^{-1})	I	IX ---	II
GM	Silty gravels, gravel-sand-silt mixtures	III (177)	III (0-20)	III (60-95)	VII (5×10^{-4})	VI	VII (68)	IV
GC	Clayey gravels, gravel-sand-clay mixtures	V (150)	VI (10-50)	V (50-90)	V (10^{-4})	VIII	IV ---	VII
SW	Well-graded sands, gravelly sands, little or no fines	I (>200)	II (0-10)	II (95-100)	IX (10^{-3})	IV	VIII (60)	III
SP	Poorly graded sands, gravelly sands, little or no fines	I (>200)	II (0-10)	II (95-100)	XI (5×10^{-2})	II	VII ---	IV
SM	Silty sands, sand-silt mixtures	II (179)	IV (0-20)	IV (60-95)	VIII (10^{-3})	V	VI (112)	V
SC	Clayey sands, sand-clay mixtures	IV (157)	VII (10-50)	VI (50-90)	VI (2×10^{-4})	VII	V ---	VI
ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands, or clayey silts with slight plasticity	IX (104)	V (0-20)	VII (0-60)	IV (10^{-5})	IX	III (180)	VIII
CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays	VII (111)	VIII (10-50)	VIII (0-55)	II (3×10^{-8})	XI	II (180)	IX
OL	Organic silts and organic silty clays of low plasticity	X (64)	V (0-20)	VII (0-60)	---	---	---	---
MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts	VIII (107)	IX (50-100)	IX (0-50)	III (10^{-7})	X	---	---
CH	Inorganic clays of high plasticity, fat clays	VI (145)	X (50-100)	X (0-50)	I (10^{-9})	XII	I (200-400+)	X
OH	Organic clays of medium to high plasticity, organic silts	XI (62)	---	---	---	---	---	---
Pt	Peat and other highly organic soils	XII (46)	---	---	---	---	---	---

Same k values as for Impede Water Percolation

Same H_c values as for Impede Gas Migration

(continued)

TABLE 6 (continued)

USCS Symbol	Fire Resistance	Erosion Control		Dust Control	Reduce Freeze Action		Crack Resistance (Expansion, %)
		Water (K-Factor)*	Wind (Sand-Gravel, %)		Fast Freeze (H_c, cm)*	Saturation (Heave, mm/day)	
GW	Same as Impede Gas Migration	I (< .05)	I (95-100)	Same ranking and values as for Wind Erosion Control	X	I (0.1-3)	I (0)
GP		I ---	I (95-100)		IX	I (0.1-3)	I (0)
GM		IV ---	III (60-95)		VII	IV (0.4-4)	III ---
GC		III ---	V (50-90)		IV	VII (1-8)	V ---
SW		II (.05)	II (95-100)		VIII	II (0.2-2)	I (0)
SP		II ---	II (95-100)		VII	II (0.2-2)	I (0)
SM		VI (.12-.27)	IV (60-95)		VI	V (0.2-7)	II ---
SC		VII (.14-.27)	VI (50-90)		V	VI (1-7)	IV ---
ML		XIII (.60)	VII (0-60)		III	X (2-27)	VI ---
CL		XII (.28-.48)	VIII (0-55)		II	VIII (1-6)	VIII (1-10)
OL		XI (.21-.29)	VII (0-60)		---	VIII ---	VII ---
MH		X (.25)	IX (0-50)		---	IX ---	IX ---
CH		IX (.13-.29)	X (0-50)		I	III (0.8)	X (>10)
OH		VIII ---	---		---	---	IX ---
Pt		V (.13)	---		---	---	---

(continued)

TABLE 6 (continued)

USCS Symbol	Side Slope			Discourage Burrowing	Impede Vector Emergence	Discourage Birds	Support Vegetation	Future Use	
	Stability	Seepage	Drainage					Natural	Foundation
GW	Determine on basis of laboratory testing	Same ranking and values as for Impede Water Percolation	Same ranking and values as for Assist Water Percolation	Same ranking and values as for Slipperiness Trafficability	X	All soils are suitable	X	Same ranking as for Support Vegetation	Same ranking and values as for Go-No Go Trafficability
GP					X		X		
GM					VIII		VI		
GC					V		V		
SW					IX		IX		
SP					IX		IX		
SM					VII		II		
SC					IV		I		
ML					VI		III		
CL					III		VII		
OL					VI		IV		
MH					II		IV		
CH					I		VIII		
OH					---		VIII		
Pt					---		III		

* RCI is rating cone index, k is coefficient of permeability, H_c is capillary head, and K-Factor is the soil erodibility factor. The ratings I to XIII are for best through poorest in performing the specified cover function.

provided, but considerable subjectivity has been required in estimating ranges since the grain size (i.e., clay content) is not an essential part of the USCS, the system used in the table.

Ranking for slipperiness trafficability in column 3 is similar to ranking in the previous column though based on a different parameter, sand and gravel percentage. Sand and gravel components decrease the slipperiness, i.e., improve the quality of soil from that functional point of view, by increasing frictional resistance. Attention is called to the fact that all three trafficability functions provide approximately the same soil ranking.

Water percolation is addressed in columns 4 and 5. The best parameter for judging relative effectiveness for water percolation is the coefficient of permeability k, although it specifically reflects water movement in a saturated condition. The rankings in columns 4 and 5 are diametrically opposed, since one reflects impeded percolation and the other assisted percolation.

Gas migration is addressed in columns 6 and 7 from contrasting viewpoints of impeded and assisted flow. The parameter on which the ranking is partly based is the capillary head H_c of the soil. This parameter reflects the tenacity with which the soil holds water. The relationship between contained water and the ability of gas to move through the soil is discussed in Section 9. Column 8 shows the fire resistance ranking of soils. The ranking is the same as that for impeded gas migration in column 6, since fire resistance is increased if gas movement is impeded (see Section 17).

Two types of erosion control are considered in columns 9 and 10. Soils are rated for resistance to water erosion on the basis of values of the USDA soil erodibility K-factor. For wind erosion resistance, soils are rated according to the sand and gravel content. The basis for the ranking and choice of quantitative parameters is made clear by discussions in Sections 10 and 11. Column 11 is concerned with dust control. Fine-grained particles are essential for dust, so that the appropriate quantitative rating parameter is considered to be the sand and gravel content. The ranking, therefore, is the same as for wind erosion control.

Columns 12 and 13 concern cover functions of reducing freeze action. The fast freezing/fast thawing aspects, which also involve the tendency to freeze to greater depths, give soil ratings I to X based on H_c. The H_c values are the same as used in column 7 for assist gas migration. For the heaving aspect of freeze action, laboratory measurements are available. The quantitative parameters on which the ranking in column 13 is based are discussed and illustrated more fully in Section 16.

Ranking for crack resistance involves considerable judgment, since only a few general ranges of expansion (and contraction) percent have been estimated in the literature (see Section 18). It is, however, well known that the extreme cracking is almost restricted to soils with high clay content, and only those soils rated VIII or worse should cause much concern.

Important aspects of the side slope cover are stability, seepage, and drainage. The seepage and drainage aspects in columns 16 and 17 have rankings and rating values identical to those for impede water percolation and assist water percolation, respectively. The stability of side slopes may in some cases be a very important function of the cover. In such cases, the choice of soil should be carefully considered and based on laboratory strength tests.

As indicated in Section 20, the effectiveness of soils for discouraging burrowing animals is believed to increase with the percentage of sand content. Accordingly, the same ranking is used in column 18 as was used for slipperiness trafficability, since in both cases the important parameter is sand and gravel content. In order to impede vector emergence, a soil with a high clay content or a well-graded combination of clay and silt, with or without sand, is preferred. This quantitative parameter is approximately the same as for stickiness trafficability; therefore, the same ranking is used in column 19. Soil type is apparently not a pertinent consideration in discouraging birds, so no preference is given in Table 6.

Loamy soils are somewhat more suitable for supporting vegetation than soils at the sand, silt, and clay extremes of grain-size distribution. Thus, a ranking of cover soil for supporting vegetation in column 21 gives the high positions, somewhat subjectively, to loam and other well-graded mixtures. For the long-range future use of a landfill site for natural or parklike settings, the ranking should be the same as for supporting vegetation. Where the future use of the landfill will be to support pavement or light structures, a major concern is for high modulus. This aspect of cover soil is adequately reflected in RCI values as for go/no go trafficability (see Section 14). It should be remembered, however, that the supportive capability of the underlying solid waste is commonly the critical factor.

SECTION 5

PLACEMENT AND TREATMENT OF SOIL

After selection of the soil for covering solid waste, efforts should be directed to the most effective placement and treatment. Soil cover can be improved in several ways as it is constructed. Materials may be added for better gradation, hauling and spreading equipment can be operated beneficially, and the base or internal structure of the cover system may be improved.

COVER COMPACTION

Some compaction is almost always accomplished during the spreading of cover soil; and this densification is highly effective in producing benefits, principally increasing strength and reducing permeability. Figures 20 and 21 illustrate these effects. Various aspects of the compacting procedure are

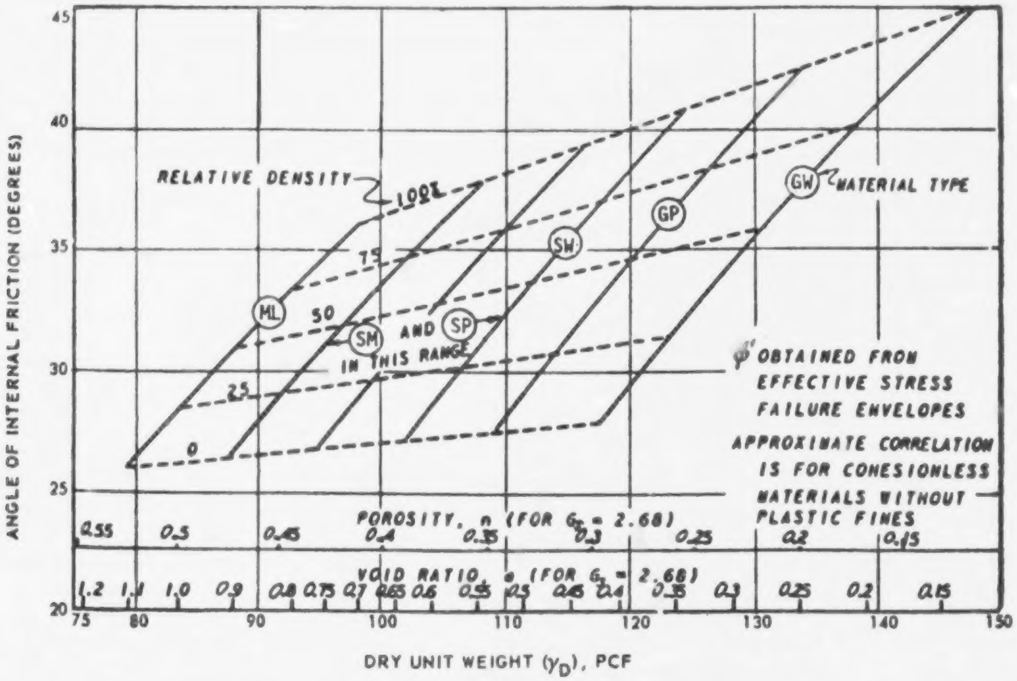


Figure 20. Relation of effective angle of internal friction to dry unit weight.[17]

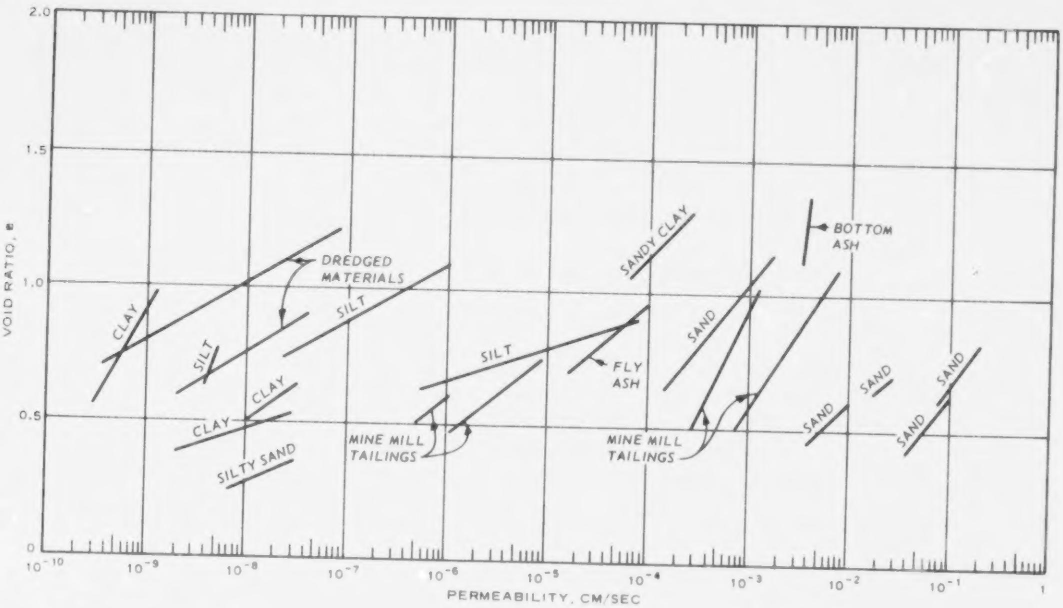


Figure 21. Coefficient of permeability of materials as affected by degree of compaction.

identified and explained below. Also see Dispersants under ADDITIVES AND CEMENTS for a means of improving compaction results.

Compacting Equipment and Passes

Special equipment for compacting is available in a variety of types, weights, and costs (Table 7). Rubber-tired rollers, sheepsfoot rollers, and

TABLE 7. LANDFILL EQUIPMENT NEEDS[3]

Solid waste handled (tons/8 hr)	Crawler loader		Crawler dozer		Rubber-tired loader	
	Flywheel horsepower	Weight* (lb)	Flywheel horsepower	Weight* (lb)	Flywheel horsepower	Weight* (lb)
0–20	<70	<20,000	<80	<15,000	<100	<20,000
20–50	70 to 100	20,000 to 25,000	80 to 110	15,000 to 20,000	100 to 120	20,000 to 22,500
50–130	100 to 130	25,000 to 32,500	110 to 130	20,000 to 25,000	120 to 150	22,500 to 27,500
130–250	150 to 190	32,500 to 45,000	150 to 180	30,000 to 35,000	150 to 190	27,500 to 35,000
250–500	combination of machines		250 to 280	47,500 to 52,000	combination of machines	
500–plus	COMBINATION OF MACHINES					

Note: Compiled from assorted promotional material from equipment manufacturers and based on ability of one machine in stated class to spread, compact, and cover within 300 ft of working face.

* Basic weight without bucket, blade, or other accessories.

vibratory rollers for highway construction may be directly useful in operations disposing of industrial and utility wastes. High priority, well-regulated operations covering physically uniform solid waste may achieve high-quality results similar to those in highway embankments and structural foundations. Elaborate and expensive compactors are not usually so practical on municipal waste landfills, and instead special lightweight, multipurpose compactors have been developed.

Actually, the simple track-type tractor is probably most popular for covering solid waste, with tamping rollers and tired vehicles having much less popularity. A 2-yd bucket is a more or less standard accessory often preferred to the soil or garbage blade. Economics and versatility usually dictate this choice of compacting equipment. As far as the technical basis for the selection, the effectiveness in handling and compacting the solid waste is usually most important, and a compactor is seldom acquired principally for its effectiveness on cover alone.

The number of passes by the spreading and compacting equipment across the soil is a separate aspect of compaction, but closely related to the type of equipment. The equipment weight (transmitted as pressure through tracks or wheels) and the number of passes largely determine the energy of the compacting process. Unfortunately, an effort of more than two passes may be impractical to monitor and regulate at municipal landfills.

The validity of laboratory compaction tests for predicting field compaction hinges on the similarity of energy input in the two different ways. Compaction results are also affected by the soil type, but the following approximations can be made regarding field techniques for achieving about 95 percent of the standard maximum density on a solid base.

Equipment	Compacted Lift thickness in.	Passes
Sheepsfoot rollers	6	4-8
Rubber-tired rollers	10	6-12
Crawler tractors	10-12	6-8

Figure 22 based on new data for this manual indicates that soil compacted routinely over municipal waste falls below standard compaction curves. However, much of this difference results from the sponginess of solid waste below (see Base Density and Resilience) and the lesser number of passes normally undertaken. The anomalously high field compaction at the Byram landfill apparently reflects the original high density of the geological formation used as cover here.

General guidance (Figure 23) has been derived from these results regarding the field compaction effort necessary in 6-12 in. of soil cover at solid waste operations. Field dry density can be predicted from measured placement water content by using laboratory compaction curves at total blow counts

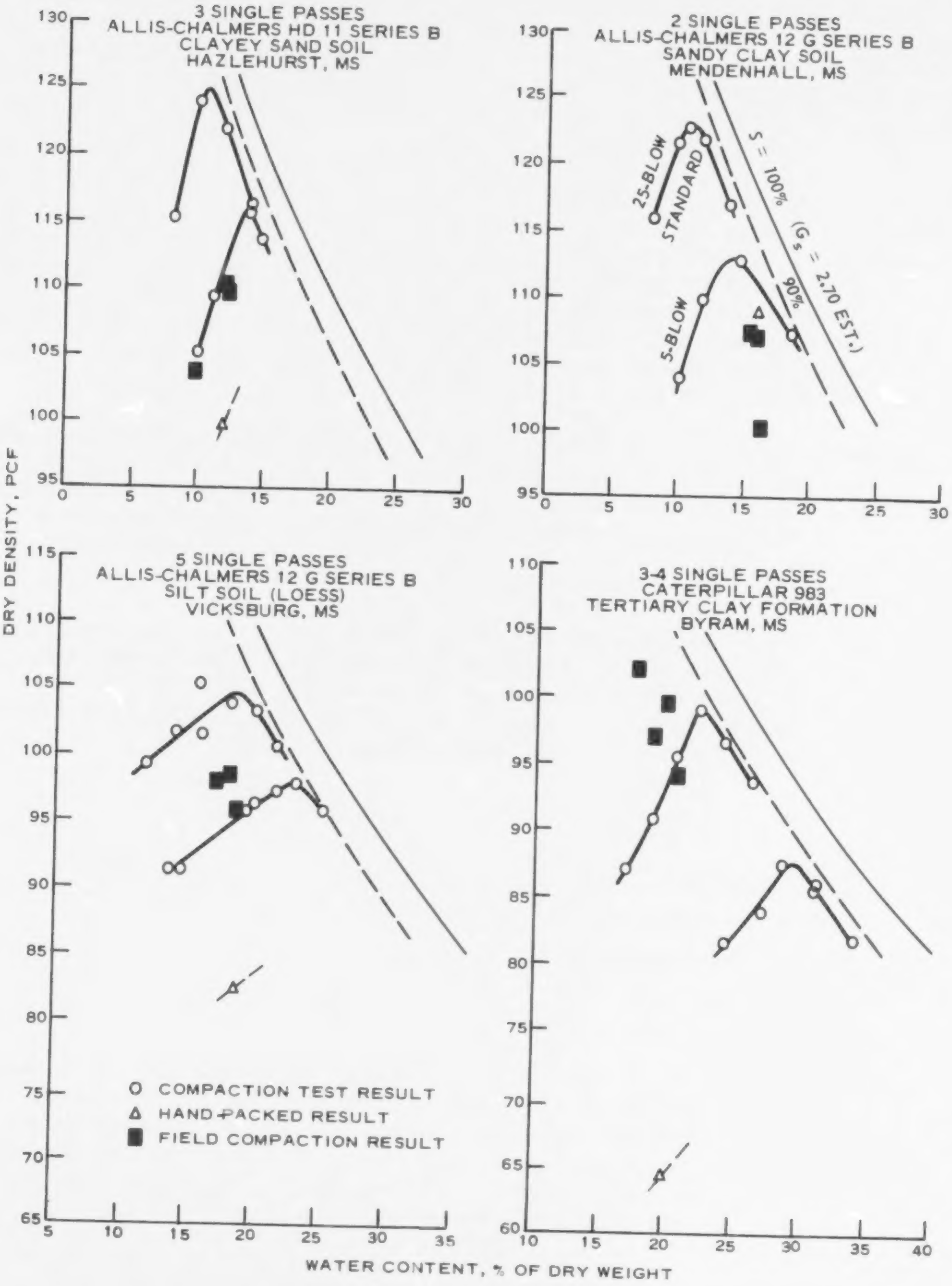


Figure 22. Cover compaction on municipal solid waste as compared to laboratory test results.

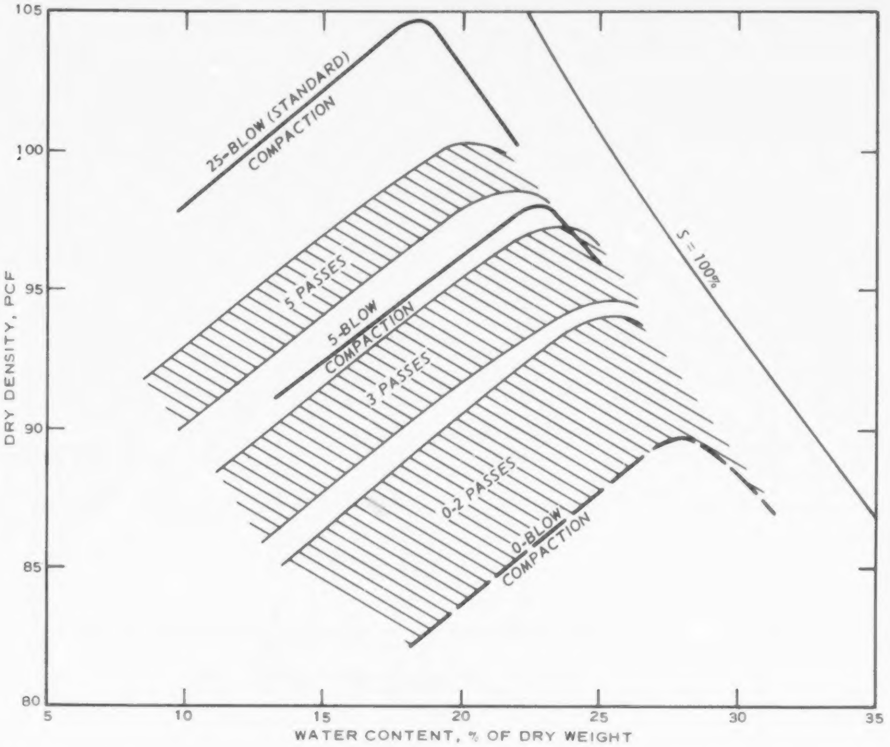


Figure 23. Schematic guidance for predicting cover compaction results with intermediate-size dozers on municipal solid waste using laboratory test results.

corresponding to the expected number of equipment passes. For example, at a site where the dozer makes four passes on the average, a 5-blow compaction curve should be determined by laboratory testing and be used for predictions. The curves shown in Figure 23 appear generally valid, but relations between field compaction and laboratory curves should be determined site specifically if cover density data are deemed necessary.

Soil Type

For a given compaction effort and method, the soil type largely determines maximum dry density and optimum water content. Maximum dry densities for standard compaction range from approximately 50 to 130 lb/ft^3, usually increasing as the grain-size distribution becomes more well graded. Optimum water content tends to increase as percentage of silt or clay increases. Figure 24 presents conceptually useful generalizations, but such generalized compaction curves should never be used in design as a substitute for testing the actual soil.

Figure 25 shows how variable individual landfill sites[5] can be. Nineteen distinct groups of soil samples from landfill sites (see Section 1) are

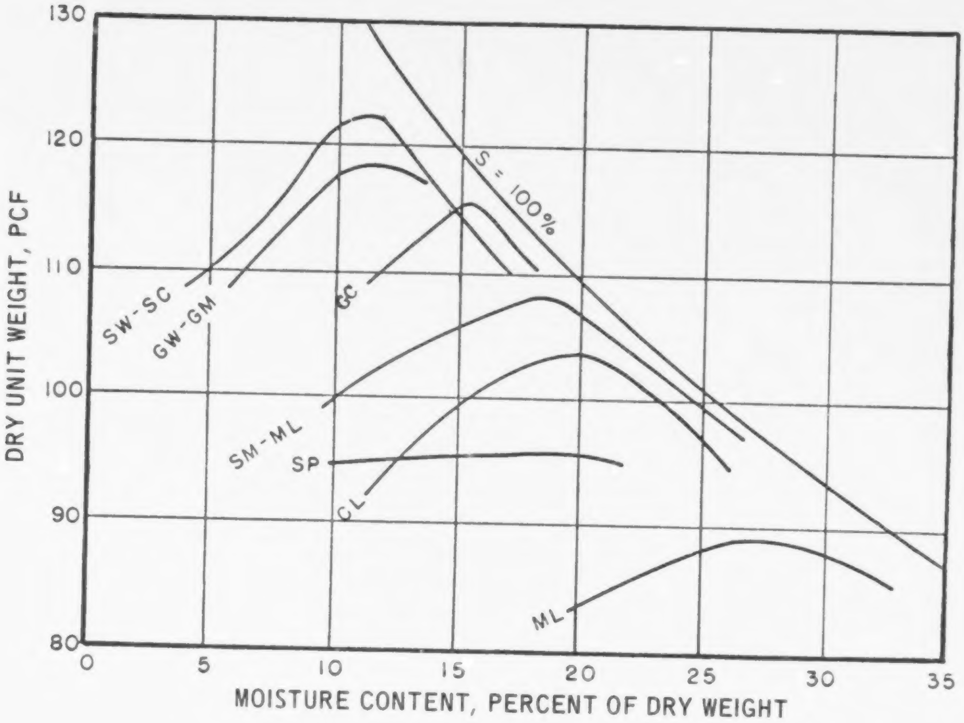


Figure 24. Example standard compaction curves for various soil types.[5]

plotted according to standard laboratory compaction test results. Full compaction curves were determined, but only points of maximum density/optimum water (the top of each individual compaction curve) are shown on the figure.

The salient features of this presentation are:

a. At individual landfills two or more USCS types may be present, e.g., Reed Road (Houston), Texas, has separate and distinct CL and CH soils.

b. USCS types overlap considerably, e.g., all CL soils together range from 96 to 117 lb/ft^3 in maximum dry density.

c. Within a single USCS type from a single landfill site a range of values commonly occurs, e.g., the SM samples from Lexington, Massachusetts, vary from 100 to 104 lb/ft^3 in maximum dry density.

Where information on compacted density is needed, the tests should be run. Five- and fifteen-blow compaction tests are usually most appropriate since they more closely simulate a few passes of a tractor across soil on waste as discussed above.

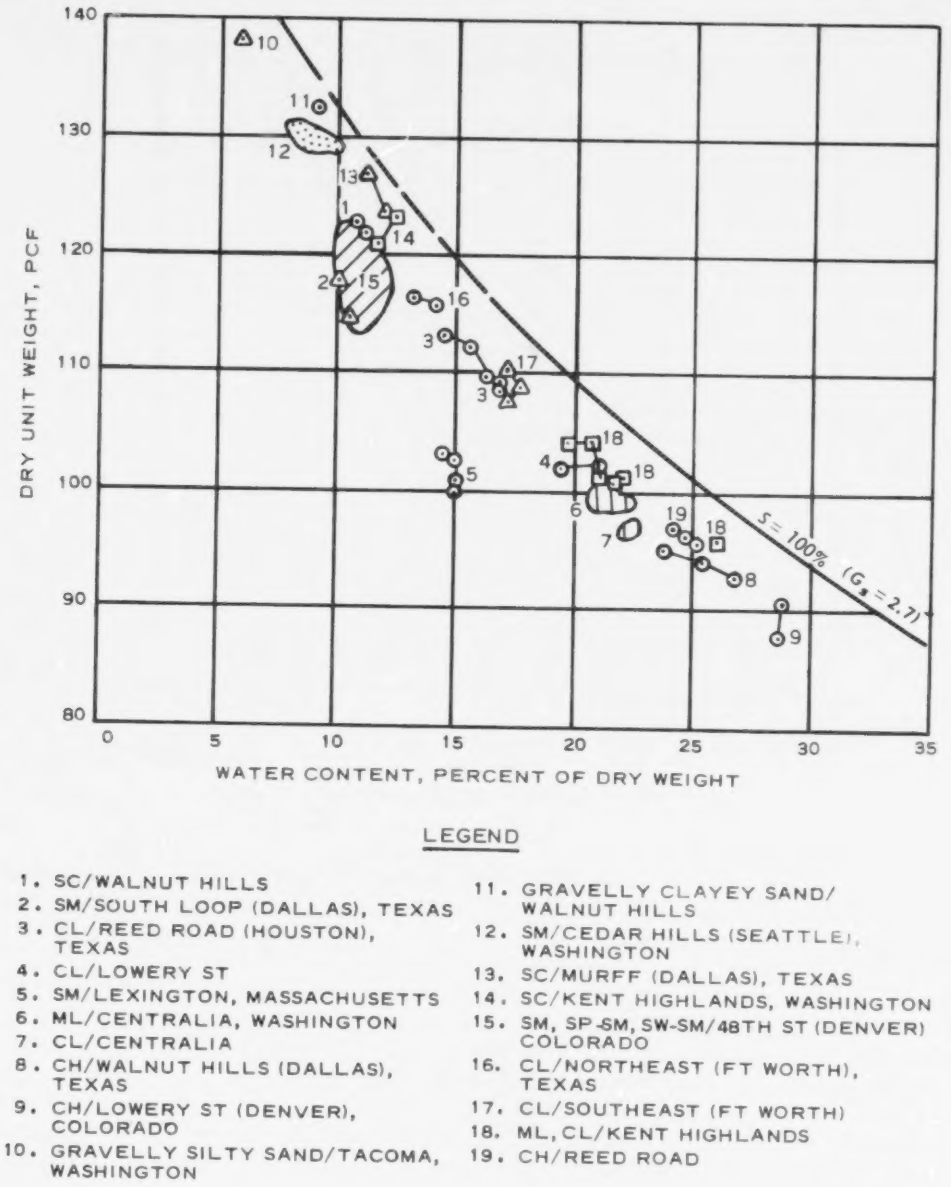
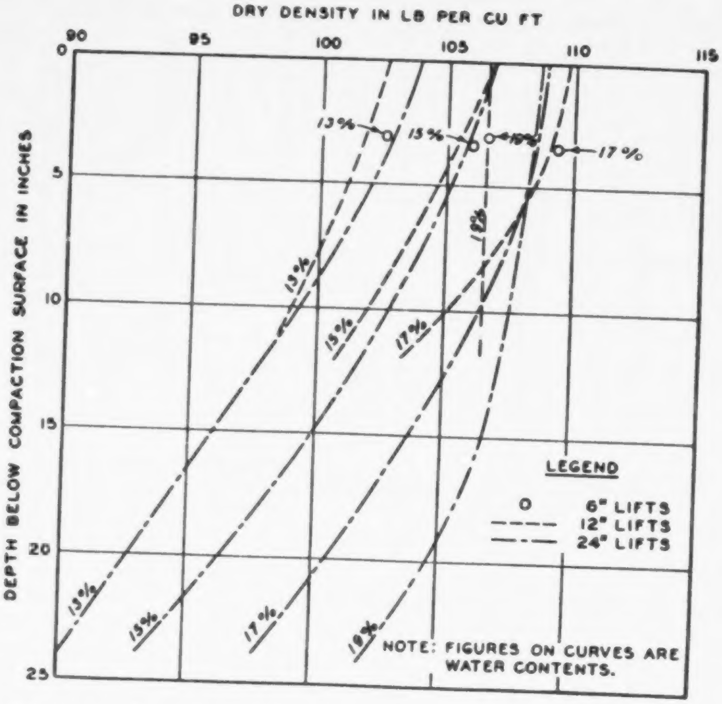


Figure 25. Points of maximum dry density and optimum water content by standard compaction test for soils used as cover on sanitary landfills.

Lift Thickness

The overall degree of compaction is markedly influenced by the lift thickness, i.e., placed and compacted in one operation. Figure 26 reveals the characteristic decrease in unit weight with depth. Accordingly, relatively



NOTE: FIGURES ON CURVES ARE WATER CONTENTS.

Figure 26. Effect of compaction lift thickness on soil density for eight coverages of a 90-psi roller.[18]

thin-lift construction is recommended for cover in order to achieve relatively high overall density with its beneficial effects. Ordinarily, lifts should be 1 ft or less in loose thickness.

Compaction in thin-lifts on a spongy waste, however, can lead to excessive cracking (Figure 27) Commonly, the passing equipment causes wavelike deformation in adjacent parts of the cover. Daily cover cracked in this way is not so effective. Percolation of rainwater will be high, at least initially, since the water can move directly into large open cracks that pass through the cover. Addition of a second lift on an as-needed basis should be considered to rectify this situation whenever weather conditions threaten a period of high potential percolation.

Water Content

Natural water content of soil often approaches the optimum for compaction; therefore, it may be unnecessary to modify the water content. Where compaction tests indicate, however, that the natural water content is not appropriate to high-density compaction, water may be added by sprinkling or subtracted by spreading to dry before using. Spreading and drying are expensive, and it may be advantageous to excavate and stockpile in fair weather and add water as appropriate later when used.

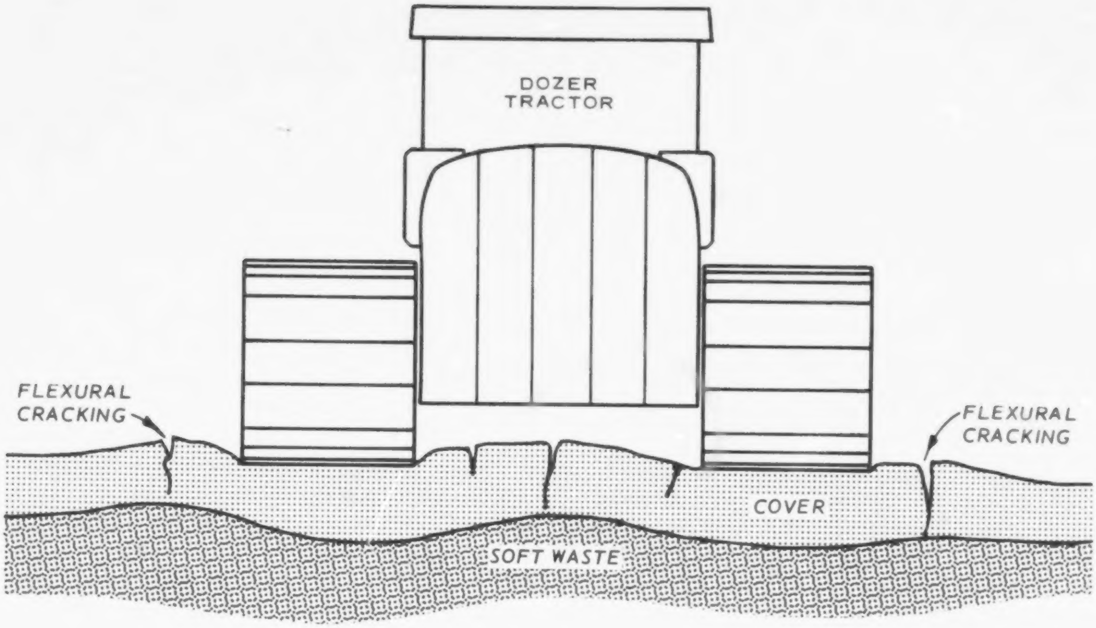


Figure 27. Cracking from flexing of cover on spongy base of solid waste.

Field compaction sometimes achieves maximum density at a water content somewhat greater than optimum indicated by a comparable compaction test, and it is sometimes specified that departures from optimum water content be on the wet side. However, compaction on the dry side often achieves somewhat greater strength.[19] Also, compaction on the dry side may be best with swelling soils since the water imbibed later will promote further swelling and work against the formation of cracks (except at the surface).

Lacking compaction test data, one may estimate standard optimum water by wetting soil until a compact ball can be formed manually. No water should be squeezed out, and the soil should retain its dense structure after opening the fist.[20]

Base Density and Resilience

A solid base on which to compact each lift is essential for ordinary soil construction. Municipal and some industrial wastes are deficient in comparison, and the designer must settle for the best compaction of waste within reason. He must also allow for the consequences of a spongy base and the settlements that inevitably will follow. Where these effects are to be minimized, the designer should specify either the actual compactive effort (equipment and number of passes) or some indicator of satisfactory results being achieved, e.g., compacted density of 850 lb/yd^3 for waste running 500 lb/yd^3 loose.[7]

At the present state of the art, specifying a conservative compactive effort is most logical since field tests for determining bulk density of waste are not routinely conducted. One might specify four passes of equipment as a first cut until experience indicates a change is warranted. Additional reduction in sponginess and settlement can be achieved by mixing soil or granular waste into the soft waste during spreading. Reducing the thickness of each soft waste lift should also help. Baling of solid waste might be considered for even better results.

SOIL BLENDING

Soil blending increases expense of covering waste and, therefore, has usually not been duly considered previously. The benefits derived from blending, however, are sometimes dramatic through the alteration of grain-size distribution or average grain size.

Well-graded soils, i.e., with a wide range of grain sizes, have relatively low k values and are generally desirable for the purpose of minimizing infiltration. If well-graded soils are not available nearby, but coarse- and fine-grained soils are, blending may provide an acceptable product besides an increased source supply. The procedure is effective only for increasing impedance to water movement since a broadening of the grain-size distribution almost always results. Of course, a thorough review of other options should be made before proceeding on a large scale. Blending may be accomplished in place using a blade or harrow.

Gravel Additions

Figure 28 shows by example the effect on maximum compacted density of adding gravel to a finer soil; similar effects can be expected from other coarse materials, such as waste crushed slag. Density is increased by any

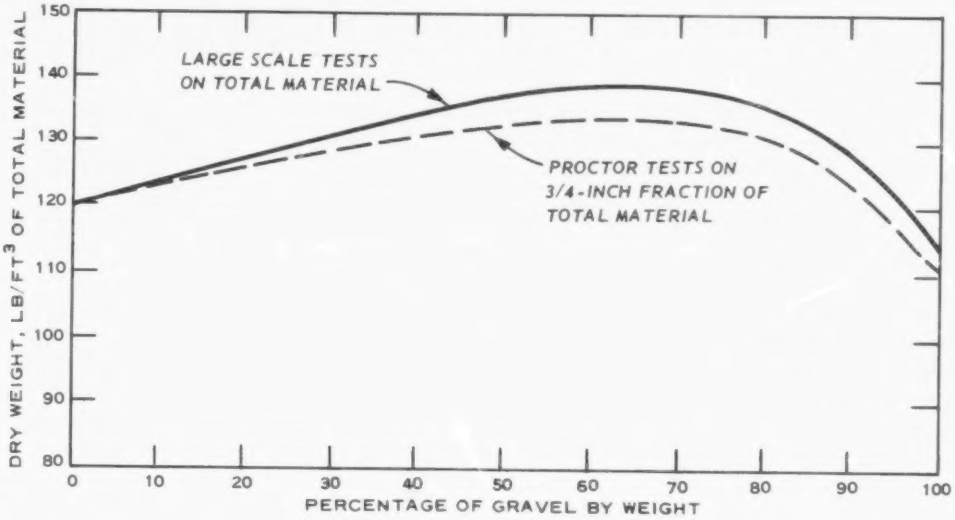


Figure 28. Effect of gravel additions to silt.[21]

addition except for mixtures with more than 95 percent gravel. These results were produced in a large compaction mold to accommodate gravel sizes, but the tests involved about the same input energy as standard compaction (see Section 3) and, therefore, are comparable to testing procedures outlined in this manual.

Effects of gravel additions on permeability have been measured in the laboratory also.[22] Tests reveal that k drops with addition of gravel to sand to about one-seventh the value of the sand alone. This effect remains about the same over the range of gravel contents of 20 to 65 percent. For mixtures containing more than 65 percent gravel, the k increases again because sand is insufficient to fill space between pebbles.

Sand- and Silt-size Additions

Additions of sand or silt should prove beneficial to cover where the grain size effectively supplements the distributions of natural soils, especially where reduced percolation is desirable. Strength is also enhanced upon compaction. Other benefits from additions of sand are potential savings in spreading and compacting costs where the original soil is clay-rich and therefore sticky or slippery when wet. Granular materials may also serve to condition certain soils to support vegetation.

The use of sandy and silty material locally may offer a convenient way of disposing of certain granular wastes. Foundry sand, washed gravel tailings, incinerator waste, and coarse tailings from mine mills are all prospective additions provided they have minimal pollution potential. Large amounts of silt-size fly ash and other furnace products are generated throughout the United States, and their use as additions to cover should be considered (also see ADDITIVES AND CEMENTS).

Clay Additions

The addition of clayey soils produces particularly dramatic reduction of k . Certain operational difficulties should be expected with clayey soils that tend to contain considerable water and therefore may be difficult to handle. It may be appropriate to excavate blending clays through relatively dry spells, store, and then incorporate during favored times of the year. Harrowing will usually be necessary. Elsewhere, it may be advantageous to use commercially available clay. Sacked bentonite should be available at modest cost in dry form suitable for rapid and inexpensive incorporation. Each case will have to be evaluated for cost and desired beneficial effect.

ADDITIVES AND CEMENTS

In distinction from nonsoil systems described in Section 6, additives and cements are defined as synthetic materials added in relatively small amounts to soil to achieve beneficial effects. One may distinguish strengthening cements or stabilizers, dispersants, freeze-point suppressants, water repellants, and dust palliatives. Factors that enter into determining the cost effectiveness of additives and cements are their relatively high unit cost, manner of addition or incorporation, and duration of effect. A major concern in using any cover system with increased strength is the remaining susceptibility to cracking as a result of differential settlement or environmental deterioration, such as freeze-thaw; plans for patching repairs are essential. Table 8 provides some guidance in choosing among three popular stabilizing additives/cements.

TABLE 8. GUIDANCE FOR SELECTING SOIL STABILIZER[23]

SOILS CLASS	TYPE STABILIZING AGENT RECOMMENDED	RESTRICTION ON LL, PL, AND PI OF SOILS	RESTRICTION ON (-200 MATL)	REMARKS
SW OR SP	(a) BITUMINOUS			
	(b) PORTLAND CEMENT			
SW-SM OR SP-SM OR SW-SC OR SP-SC	(a) BITUMINOUS	PI NOT TO EXCEED 10		
	(b) PORTLAND CEMENT	PI NOT TO EXCEED 30		
	(c) LIME	PI NOT LESS THAN 12		
SM OR SC OR SM-SC	(a) BITUMINOUS	PI NOT TO EXCEED 10	NOT TO EXCEED 30% BY WT	
	(b) PORTLAND CEMENT	PI NOT TO EXCEED NO. IND BY EQ $20 + \frac{50 - \text{FINES CONT}}{4}$		
	(c) LIME	PI NOT LESS THAN 12		
GW OR GP	(a) BITUMINOUS			WELL-GRADED MATL ONLY
	(b) PORTLAND CEMENT			MATL SHOULD CONTAIN AT LEAST 45% BY WT OF MATL PASSING NO. 4 SIEVE
GW-GM OR GP-GM OR GW-GC OR GP-GC	(a) BITUMINOUS	PI NOT TO EXCEED 10		WELL-GRADED MATL ONLY
	(b) PORTLAND CEMENT	PI NOT TO EXCEED 30		MATL SHOULD CONTAIN AT LEAST 45% BY WT OF MATL PASSING NO. 4 SIEVE
	(c) LIME	PI NOT LESS THAN 12		
GM OR GC OR GM-GC	(a) BITUMINOUS	PI NOT TO EXCEED 10	NOT TO EXCEED 30% BY WT	WELL-GRADED MATL ONLY
	(b) PORTLAND CEMENT	PI NOT TO EXCEED NO. IND BY EQ $20 + \frac{50 - \text{FINES CONT}}{4}$		MATL SHOULD CONTAIN AT LEAST 45% BY WT OF MATL PASSING NO. 4 SIEVE
	(c) LIME	PI NOT LESS THAN 12		
CH OR CL OR MH OR ML OR OH OR OL OR ML-CL	(a) PORTLAND CEMENT	LL LESS THAN 40 AND PI LESS THAN 20		ORGANIC AND STRONGLY ACID SOILS FALLING WITHIN THIS AREA ARE NOT SUSCEPTIBLE OF STABILIZATION BY ORDINARY MEANS
	(b) LIME			

Cemented Soil

Cemented soil systems have been developed for lining canals, surfacing roads, and strengthening embankments and subgrades, and they presumably can perform as well locally for covering solid waste (Figures 29 and 30).

Soil-cement. Soil-cement is composed of sandy soil, portland cement, and water that have reacted and hardened. About 8 percent of dry cement is incorporated in place and compacted after water is added to about optimum content. Premixing and placement wet is another method that seems less amenable to covering waste because of extra costs, except possibly on steep slopes. Somewhat higher cement content is needed in poorly graded soils or where fines are lacking, but correspondingly less for well-graded mixtures. Figure 29 shows by example how a U. S. Bureau of Reclamation criterion of 6 percent weight loss is applied to freeze-thaw and wet-dry testing results to establish cement content for lining jobs where the environment is severely cold or alternately wet and dry.

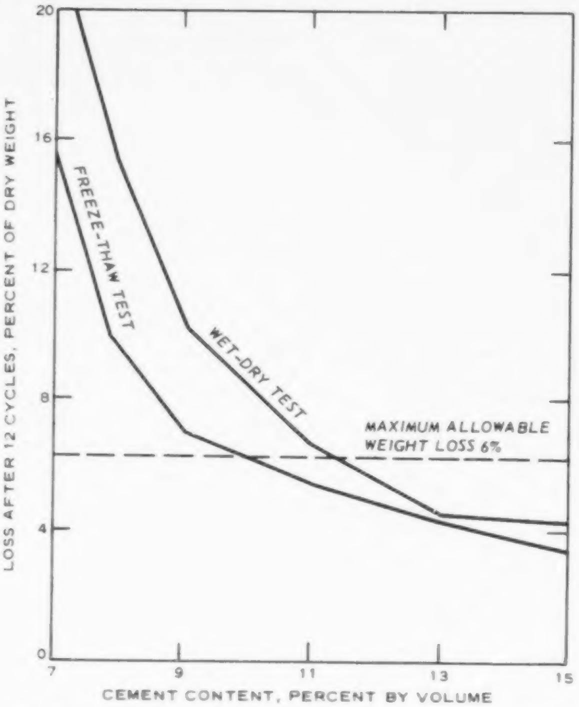


Figure 29. Example of freeze-thaw and wet-dry durability test data and soil-cement design criterion.[24]

While mixing and incorporating with rotary hoe or tiller, the operator should add water to the desired amount; then compact within about 1 hr. Sprinkling intermittently helps during a curing period of several days, and a cover of wet soil achieves further curing. The last step may be combined with preparation and seeding for vegetation with sufficient planning. Soil-cement may be vulnerable to deterioration where organic and sulfurous products of the waste can gain access.

Soil-bitumen. Bitumen stabilizes sandy soils by cementing and waterproofing. An optimum content increases the cohesion of the soil, yet does not separate grains enough to reduce frictional strength. From 4 to 8 percent bitumen (soil dry weight basis) is recommended as a first cut for sandy loam to be refined subsequently by testing mixtures of various contents. Sand should require somewhat less bitumen.

The mixing procedure should be developed site-specifically. Water is added as needed to the soil for desired compaction; then add cutback or emulsified asphalt or tar. Further mixing, spreading, and compacting should be accomplished in relatively short time. It may be expeditious to spread before adding the bitumen (and disking). The critical time from final mixing to compaction is thereby reduced to as little as a few minutes.

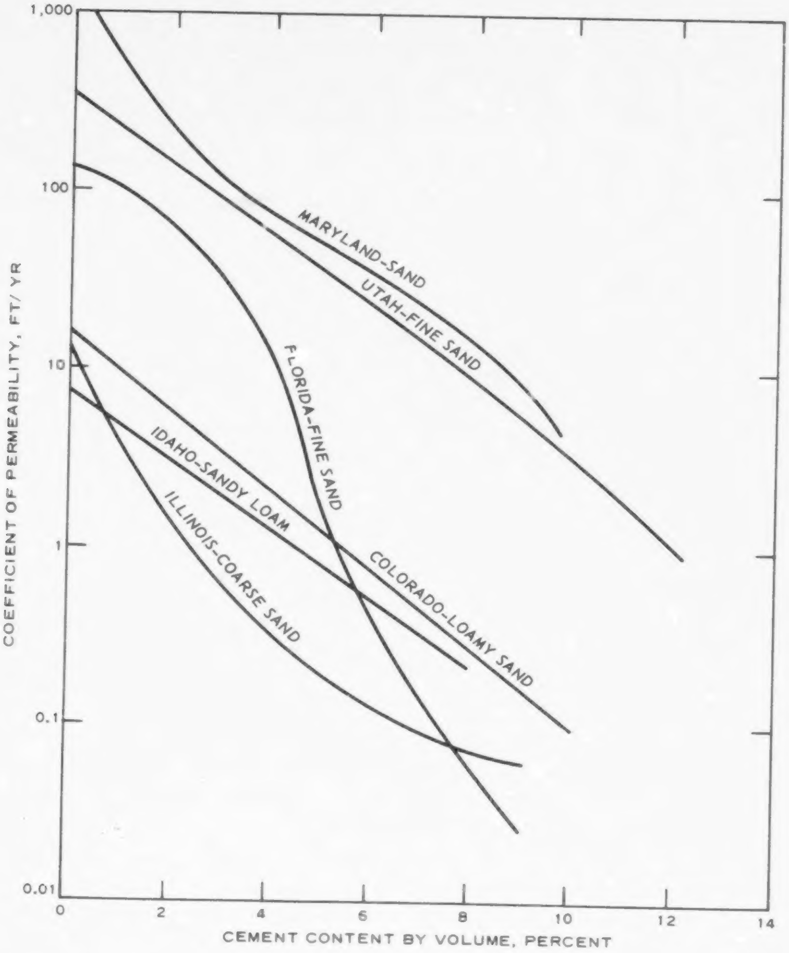


Figure 30. Permeability of some cement-treated soils.[24]

The longevity of effectiveness of soil-bitumen is a factor that deserves careful consideration. Volatiles eventually leak away and leave the system in an altered, sometimes degraded, condition. Cracking will also reduce integrity, and patching may eventually become necessary.

Modified Soils

Cement-treated soil. Incorporation of as little as 1 percent of portland cement has been shown to have stabilizing effects on granular soil, and cement-stabilized soils are used occasionally for lining embankments and drainage ditches. The effect in laboratory tests is illustrated in Figure 31. However, other environment influences, such as freeze-thaw, can reduce the practicability of the technique (see Soil-cement).

Lime-treated soil. Lime (calcium oxide or hydroxide) is principally

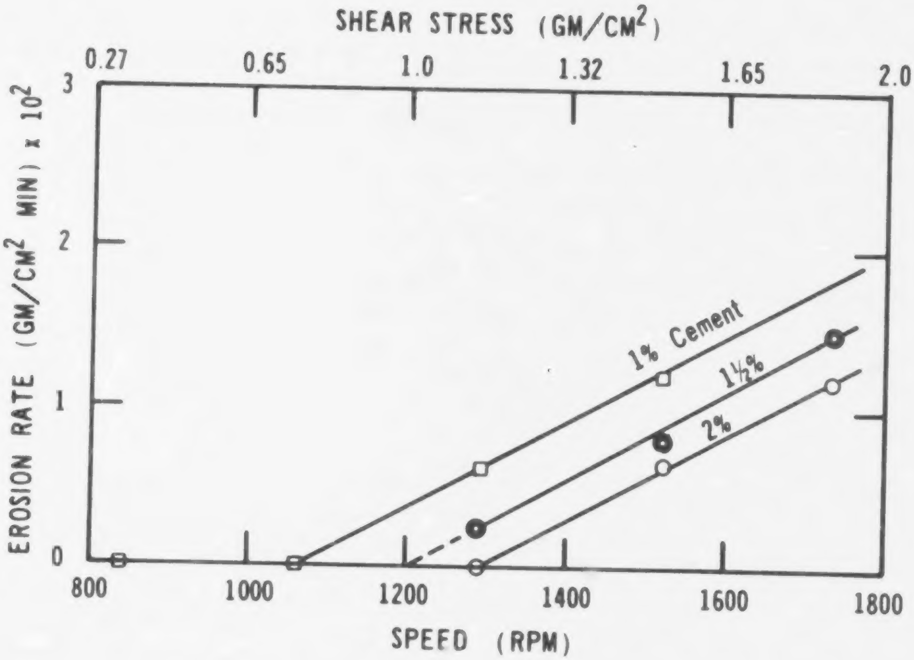


Figure 31. Erosion rates for cement-stabilized sandy soil.[25] (Reproduced by permission of Transportation Research Board.)

mixed into clayey soils for its effects as a flocculant or base exchanger (see Swell Reducers). However, lime also promotes some beneficial pozzolanic reaction in fine, cohesive soils,[26] and strengthening may continue for many weeks of curing. See Table 8 for applicability of lime versus other stabilizers. The following approximate lime percentages have been suggested as a rough guide for selecting lime contents.

Soil Type	Approximate Percentage Hydrated Lime	Quicklime
Clayey gravels (GC, GM-GC)	2-4	2-3
Silty clays (CL)	5-10	3-8
Clays (CH)	3-8	3-6

These percentages may amount to overdesign in some solid waste applications, so the designer should consider smaller additions and evaluate test trials on the basis of measured high pH.[27]

Fly ash-lime (or cement)-treated soil. Fly ash is attractive as an additive to soil because of its pozzolanic properties,[28] i.e., though not a cement in itself, fly ash develops cementitious properties with lime or cement and water. Accordingly, a small amount of lime or portland cement should be included unless self-hardening has been confirmed by test or previous experience with the particular fly ash (see Fly ash-treated soil).

Proportioning of soil, lime, and fly ash is dictated by economy and desired properties in normal soil stabilization. In solid waste disposal, a scarcity of cover soil and a growing surplus of fly ash nearby may obviate such normal concerns and lead to the practice of using as much fly ash as can be tolerated (see Section 6). Thus, a normal mix for stabilization with the common lime to fly ash ratio of 1:4 may contain about 20 percent fly ash, 5 percent lime, and 75 percent soil, but mixtures placed over waste may be just as effective at 60 percent fly ash, 5 percent lime, and 35 percent sand. Any accompanying sacrifice in strength should not be critical in landfill covering.

Sands and gravels are more suitable for lime-fly ash stabilization than are fine-grained, plastic soils. The resulting broadened grain-size gradation should be conducive to dense compaction and best reaction, although the formation of cementitious products works against attainment of densities otherwise possible. Water content often should be slightly below optimum for maximum density. Mixing is important as with other additions, and a rotary tiller may be very effective. Preferably, water should be added only after mixing dry ingredients, and compaction should follow as soon as possible. Traffic should be prohibited on the cover for several weeks if maximum curing is desired.

Fly ash-treated soil.* Some fly ashes possess moderate self-hardening characteristics when moistened and compacted[29] and, therefore, offer promise alone as major additions to cover over waste. This phenomenon is partly due to the free lime content of the ash itself. Laboratory tests or field trials will be necessary to establish such useful peculiarities of specific fly ash sources where previous experience is lacking. Tests also establish optimum mixtures for strength, durability, etc.

Fly ash from western, low-sulfur coal often contains high calcium.[30] Such material,[31] (mixed with clay or with sand) may heat in reaction upon wetting and cause major increase in strength and decrease in k. Reduction in k of as much as a thousand fold[31] for treated sand is probably partly due to altered grain size and distribution as explained under SOIL BLENDING rather than to development of cementation.

Fly ash-lime (or cement)-sulfate-treated soil. This mixture is proposed here as a locally viable option for covering waste following research on the uses of fly ash-lime-sulfate (or sulfite).[32] See Modified Fly Ash under WASTE MATERIALS for additional information.

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* The pollution potential of fly ash has not been entirely defined, and its use in cover at a landfill should be prefaced on favorable conclusions of environmental impact studies.

Other treated soil systems. As witnessed by the proposed beneficial use of waste sulfates and sulfite, new developments in treating soil will continue to appear for consideration. Materials that deserve serious consideration and trial should possess most of the following attributes:

a. Replace scarce soil.

b. Improve physical properties of soil; or at least develop no adverse properties.

c. Have low pollution potential.

d. Are wastes themselves.

e. Reduce expenses.

Dispersants

Several soluble salts act as dispersing agents and are recommended for improving soil compaction and reducing k . The treatment is primarily for fine-grained soils containing clay minerals. Better compaction can be achieved on coarse-grained soils by other means, such as blending in fine material (see SOIL BLENDING)

Dispersion (deflocculation) involves the breakdown of clayey aggregates into the individual mineral particles. The effect is to increase dry unit weight, to lower permeability, and incidently, to facilitate compaction. Dispersing agents are evaluated qualitatively by adding a small amount to a ball of moist soil and noticing whether the soil becomes wetter. Soil should be at least 15 percent finer than 0.002 mm and 50 percent finer than 0.074 mm to be significantly affected by dispersing agents.[33] It has also been found that montmorillonite is much more susceptible than kaolinite or illite, and treatment of many soils in the northeastern and midwestern United States would be questionable. Testing should be undertaken prior to specifying the use of dispersants in these regions.

Three dispersing agents have been found notably effective.[33] Common sodium chloride produces satisfactory results in many cases and is inexpensive. Tetrasodium pyrophosphate and sodium polyphosphate appear to have slight advantages in many cases over sodium chloride.[33] Sodium carbonate or bicarbonate is also effective. Applications are approximately 0.20 to 0.33 lb/ft^2 for salt and 0.05 lb/ft^2 for sodium polyphosphate. The application for sodium chloride amounts to about 0.1 percent of dry soil weight for a 6-in. compacted layer. Costs of such chemically sealed soil linings for ponds were estimated to range 300-3000 dollars/acre in 1963.[33] For a solid waste cover, cost would be considerably less since extra spreading and compacting would be insignificant and lesser additions should be adequate.

Table 9 shows the effectiveness of treatments as far as reducing permeability. Disadvantages of the use of dispersing agents are increased susceptibility to erosion and to cracking due to the enhanced shrink/swell behavior. It follows from these known characteristics that dispersed (treated) silt and

TABLE 9. EXAMPLE EFFECTS OF TSPP AND NaCl* ON COMPACTION AND PERMEABILITY[33]

Soil Class	Location	Percent Finer Than		Coefficient of Permeability, ft/day				
		0.002 mm	200 mesh	85 Percent Standard Density no chemical	85 Percent Standard Density + TSPP	90 Percent Standard Density + TSPP	85 Percent Standard Density + NaCl	90 Percent Standard Density + NaCl
ML	New York	16	50	0.1	0.001	0.00001		
SC-SM	Virginia	17	48	0.137	0.028	0.0001		
SM-ML	Pennsylvania	14	50	0.06	0.004	0.0002		
CL	New Jersey	28	80	1.19	0.112	0.0001		
CL	Virginia	45	90	0.50	0.136	0.0001		
CL-ML	Virginia	20	90	0.02	0.001	0.0003		
CL	Virginia	33	85	0.01	0.001	0.00001		
CL	Pennsylvania	22	70	0.05			0.01	0.0013
CL	Texas	30	70	0.03			0.005	0.00001
CH	Texas	40	85	0.14			0.002	0.0008
CL	Texas	27	55	0.95			0.002	0.0001
CL	Colorado	32	75				0.072	0.004

---

* TSPP is tetrasodium pyrophosphate, and NaCl is sodium chloride.

clay may tend to erode and migrate downward into waste cells and leave the cover in a degraded condition. Therefore, the specification of use of dispersants should be preceded by on-site experimentation or trial revealing any consequences besides densification. Both erosion and shrink-swell can be reduced by covering the treated soil with a protective layer that will support vegetation. Conversely, the placement of a sand or silt layer before (below) the dispersed clay layer should largely eliminate the problem by slowing internal erosion and allowing the clay layer to deform and reseal itself. Such a combination of filter layer (see LAYERING) with overlying dispersed clay layer has been used to seal a leaky irrigation canal.[16]

Swell Reducers

Lime is the principal additive for reducing shrink/swell behavior in clay-rich soils. About 5 percent is optimum for effecting ion exchange (calcium for sodium), flocculation, and cementation. Quicklime contains more calcium and, therefore, is preferred to hydrated lime by some users provided a mellowing period is allowed for homogenization. See Modified Soils for more specific guidance on requirements.

A recommended procedure begins with restriction of the work area to a unit small enough to allow completion in a convenient work period. If cementation reaction is expected, the time period should be short, i.e., a few hours. Avoid crossing units already completed and in a curing state. Place sacks of lime on the work area at spacing to meet designed mix ratio. Open sacks and distribute; then mix dry with a harrow. Add water in increments of about 0.5-1.0 gal/yd^2, followed by more harrowing. Bring water to or slightly above optimum and hold during compaction that follows. Lift thickness ordinarily should not exceed 1 ft.

Other consequences of lime treatment that should be considered are that it reduces PI, improves the agricultural grade, and increases k of the soil. The reduced PI may benefit trafficability (Section 14), but the increase in k is usually not desirable.

Freeze-point Suppressant

Poor compaction can result when soil pore water is frozen during cold weather operations. Ordinarily soils construction for roads, etc., is curtailed in the winter to avoid the poor results. Some improvements can be achieved by adding a freeze-point suppressant and may be advisable where covering operations are expected to continue during cold spells. Calcium chloride has been recommended[34] as effective, either in solution or in dry, flaked form. Treatment of the borrow area should be considered also.

Other Additives*

Hundreds of other chemicals have been proposed for their beneficial effects on soil. Some are proported to impart water repellancy and strength; others have more obscure attributes. Many of these compounds are proprietary developments and their properties and characteristics are difficult to evaluate. Table 10 provides preliminary guidance by listing chemical additives, along with some probable characteristics and applications.

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* The pollution potential of additives should be given special consideration prior to usage.

Some previous experience or assistance from authoritative sources will often be necessary for the designer to make a choice among these products; state highway departments are one possibility. Consider the following in selecting an additive: cost, ease of application, and duration of effectiveness. Many additives work for only a short period, so that rapid follow-up treatment, such as establishment of vegetation, will usually be necessary to sustain the benefits.

LAYERING

Layering is perhaps the most promising, yet presently underutilized, technique for designing final solid waste cover. By combining two or three distinct materials in layers, the designer may mobilize favorable characteristics of each together at little extra expense. The systematics are briefly set forth here. The actual designing using materials available at specific sites will test the ingenuity of the responsible engineer; therefore, high priority may be warranted. Figure 32 schematically illustrates the system.

Topsoil

A topsoil or a subsoil made amenable to supporting vegetation frequently forms the top of a layered cover system. Untreated subsoils are seldom suitable directly, so it has been necessary frequently to supplement subsoil with fertilizers, conditioners, etc., as explained in Section 19 to obtain the desired result. Loams or USCS types GM, GC, SM, SC, ML, and CL are recommended, but agronomic considerations usually prevail. The upper lift should be placed in a loose condition and not compacted.

Barrier Layer or Membrane

The primary feature in many layered systems is the barrier. This layer functions to restrict passage of water or gas. Barrier layers are almost always composed of clayey soil that has inherently low permeability; USCS types CH, CL, and SC are recommended. Soil barriers are susceptible to deterioration by cracking when exposed at the surface, so that a buffer layer is recommended to protect the clay from excessive drying.

Synthetic membranes may be used in place of soil barriers. Costs are generally high in comparison to available soils, and problems in placement or with deterioration may arise. Nevertheless, membranes are a viable option that should be considered for some special jobs. See Section 6 for a review of available membranes. Membranes should be spread carefully over the smooth buffer soil to lie in a relaxed state; about 5 percent slack is necessary with polyethylene. Manufacturer's recommendations for field splicing should be followed. Provide a trench (8 in. deep) or other anchorage at the top of any slope.

TABLE 10. CHEMICAL ADDITIVES FOR COVER SOIL

	Attribute*			
Category and Agent	Strength	Water	Dust/Wind	Comments**
Inorganic chemicals				
Calcium chloride	Yes	Yes	Yes	Maintains moisture content. Easily leached out by water.
Lime	Yes			See discussion in text.
Phosphoric acid	Yes			Cementing agent. Mixes easily with soil.
Potassium silicate			Yes	---
Sodium carbonate				See discussion in text.
Sodium chloride	Yes			Easily leached out by water.
Sodium silicate			Yes	Effective in well-graded, compacted sand.
Sodium silicate N		Yes	Yes	Forms hard crust after 1-hour cure. Effective in sands.
Sodium silicate No. 9		Yes		Effective when sprayed on. Approximate cost $0.60/gal.
Soil lok			Yes	Combination sodium silicate and calcium chloride. Effective in fine-grained soils. Forms hard surface.
Resinous materials				
Aerospray 52		Yes		Alkyd resin emulsion that forms a hard crust. Approximate cost $2.85/gal.
Aerospray 70		Yes		Polyvinyl acetate resin emulsion. Effective in sand. Approximate cost $2.50/gal.
AM-9	Yes		Yes	Blend of water-soluble acrylamide and diacrylamide. Provides flexible surface after long curing.
Amoco A	Yes			Requires moisture and temperatures above 40°F (4°C) to cure. Effective mixed with sand.
Amoco B	Yes			Fast curing resin. Effective mixed with sand.
Aniline-furfural	Yes	Yes	Yes	Provides tough surface for dry silt and clay. Soil moisture reduces final strength Toxic.
Aniline hydrochloride furfural	Yes			Nontoxic resin. Effective in highly acid or neutral soils with PI's of 3 to 20.
Aroplaz 6065		Yes		---
Aropol 7110	Yes		Yes	Unsaturated polyester resin. Significantly increases soil strength of sand, silt, or clay.
Aropol 7720 M			Yes	Unsaturated polyester resin. Effective in sand, silt, or clay.
Arothane 156		Yes		Polyurethane elastomer with rapid curing.

(Continued)

TABLE 10 (continued)

Category and Agent	Attribute*			Comments**
	Strength	Water	Dust/Wind	
Resinous materials (continued)				
Arothane 160	Yes	Yes	Yes	Polyurethane elastomer with rapid curing. Effective in clay.
Arothane 170	Yes	Yes	Yes	Similar to Arothane 160.
Ashland CR 726	Yes			Blend of resorcinol and an accelerator. Effective mixed with clay.
Base 792-D			Yes	Blend of polyvinyl resins and modifiers.
Base 792-L			Yes	Similar to Base 792-D.
Celanese 13-67-5	Yes			---
Celanese 510+872	Yes			Blend of EpiRez 510 and EpiCure 872. Effective mixed with sand.
Celanese 16-78-16	Yes			Blend of EpiRez 510, 544, and EpiCure 8701. Requires moisture to cure. Effective mixed with sand.
Celanese 16-78-1	Yes			Blend of EpiRez 510, 856, and EpiCure 87. Effective mixed with sand or clay.
Celanese 16-77-1	Yes			---
Chem-Rez 200			Yes	Furfural based rapid setting resin. Effective in sand or clay.
Chrome lignin		Yes		Risinous alkali waste and a hexavalent chromium compound in gel form.
CIBA 509+X8157/136	Yes			Blend of Araldite 509 and X8157/136. Effective mixed with clay.
CIBA 6010+X8157/136	Yes			Blend of Araldite 6010 and X8157/136. Effective with sand or clay of variable moisture content.
CIBA 6010+X8157/157	Yes			---
DCA-70	Yes		Yes	Emulsion of polyvinyl acetate and chemical modifiers. Cures in 2 to 4 hours. Can be reinforced with fiberglass filaments.
DCA-1295	Yes		Yes	Improved DCA-70. Fiberglass reinforcement may be harmful if inhaled or blown into eyes.
Dow CX-7	Yes			Blend of vinyl ester resin, benzoyl peroxide, and N. N. dimethylanitine. Fast curing. Effective mixed with sand.
Dow derakene 114	Yes			Blend of vinyl ester resin, benzoyl peroxide, and N. N. dimethylanitine. Requires moisture to cure. Effective mixed with sand or clay.
Dresinate DS-60W-80F		Yes		Thermoplastic resin. Effective in spray applications. Approximate cost $0.34/gal.
Edoco X-2111-1	Yes			Effective in sand or clay.
Emlon E-200	Yes	Yes	Yes	Water soluble resin that cures within 2 hours in combination with diethylene triamine. Effective in sand or clay.

(Continued)

TABLE 10 (continued)

Category and Agent	Attribute*			Comments**
	Strength	Water	Dust/Wind	
Resinous materials (continued)				
Epon 828		Yes	Yes	Epoxy resin with slow curing time. Penetrates sand or clay and forms a hard crust.
Epon 828+V40	Yes			Blend of Epon 828 and V40. Effective in sand or clay.
General latex-vultex	Yes			Blend of an epoxy resin and a catalyst. Causes low strength gain.
General Mills TSX-429+TSX-428	Yes			Blend of a resin and a coreactive resin. Causes low strength gain.
HK-1			Yes	1:1 mix of Base 792-D and 792-L.
HK-2	Yes		Yes	3:1 mix of Base 792-D and 792-L. Forms tough resilient film but curing can take more than 7 hours with loose sand in humid conditions.
Jones-Dabney No. 6	Yes			Blend of EpiRez 5159, 5044, and EpiCure 874. Effective in sand or clay.
Jones-Dabney No. 7	Yes			---
Lignin liquor			Yes	Resinous alkali waste and compounds.
Ligno sulfonates	Yes	Yes	Yes	See Norlig 41.
Lino-cure C		Yes		Foundry resin that forms a hard, waterproof surface when applied with ethylene glycol.
Norlig 41	Yes	Yes	Yes	Ligno sulfonate. Approximate cost $0.27/gal.
Orzan	Yes	Yes	Yes	Mixture of ligno sulfonate and chemicals. Forms shrinkage cracks when cured. May be leached out by water.
Paracol TC1842			Yes	Resin emulsion. Good results with mine tailings.
Paracol S1461			Yes	Blend of wax and resin. Effective with mine tailings. Approximate cost $0.39/gal.
Petroset RB	Yes	Yes	Yes	Emulsion of resins, elastomer, and volatile solvents. Effective in gravel and rock. Approximate cost $2/gal.
Petroset SB	Yes	Yes	Yes	Emulsion of resins, elastomer, oils, solvents, and water. Effective in particles below gravel size. Approximate cost $1.60/gal.
R 20		Yes		Sodium methyl silanolate. Nonbiogradable. Approximate cost \$0.05/yd^2 treated.
Resinox 9673		Yes		---
Resin 321		Yes		Finely powdered resinous substance. Effective in acid soils (silty clay and clayey silt).

(Continued)

TABLE 10 (continued)

Category and Agent	Attribute*			Comments**
	Strength	Water	Dust/Wind	
Resinous materials (continued)				
Soil seal			Yes	Emulsion of material copolymers in the plastic resin range. Effective in fine-grained sand.
Vinsol		Yes		Powdered resinous substance. Effective in sandy silt, silty sand, clayey silt, and clayey sand. Susceptible to microbial attack.
Vistron silmar S-3840	Yes			Modified polyester resin. Requires moisture to cure. Causes low strength gains.
Whitesides 69-Y-1	Yes			Emulsified epoxy resin. Effective mixed with clay.
Polymeric materials				
Compound SP 301		Yes		Latex copolymer emulsion. Effective in spray application. Approximate cost $1.30/gal.
Curasol AE			Yes	Polyvinyl acetate latex dispersion. Forms a hard crust. Cleanup is difficult. Approximate cost $2.60/gal.
Curasol AH			Yes	Polyvinyl acetate latex. Forms a flexible crust.
Neoprene 750	Yes		Yes	---
Petroset RB	Yes	Yes	Yes	See Resinous materials.
Petroset SB	Yes	Yes	Yes	See Resinous materials.
Petroset AX	Yes	Yes	Yes	Emulsion of elastomer, asphalt, solvents, and water.
Petroset AT	Yes	Yes	Yes	Emulsion of elastomer, oils, and water.
Polyco 2460		Yes		Styrene/butadiene latex. Effective in spray applications. Approximate cost $0.87/gal.
Surfaseal			Yes	Viscous plastic material. May require several applications, allowing drying time prior to each additional application. Approximate cost $4.40/gal.
Terra-krete			Yes	Chemicals in latex base. Forms hard surface.
Ucar 130			Yes	Polyvinyl acetate.
Vultex 1-V-10			Yes	Prevulcanized rubber latex.
White soil stabilizer		Yes		Latex polymer, effective mixed with soil. Approximate cost $4.31/gal.
Bituminous materials				
APSB (Asphalt penetrative soil binder)			Yes	Low penetration grade asphalt, kerosene, and naptha. Good penetration in impervious or tight soils. Cures in 6 to 12 hours. Flammable.

(Continued)

TABLE 10 (continued)

Category and Agent	Attribute* Strength	Water	Dust/Wind	Comments**
Bituminous materials (continued)				
Liquid shale tar (shale oil)	Yes			Effective in sand or clay.
Peneprime			Yes	Same as APSB.
Petroset AX	Yes	Yes	Yes	See *Polymeric materials*.
Miscellaneous materials				
Admex 710			Yes	---
Aggrecote 600			Yes	---
Aquatin		Yes		Concentrate of chemicals and pectin. Forms fragile crust. Stains skin, clothing, and equipment. Approximate cost $2.30/gal.
Bio-binder		Yes		For spray applications. Approximate cost $2.57/gal.
Bisphenol A			Yes	---
Calcium acrylate	Yes	Yes		Organic salt that forms strong bonds in wet, fine-grained soils.
Calcium sulfonate		Yes		---
Cyanaloc 62		Yes	Yes	---
Dust bond 100		Yes		Approximate cost $0.36/gal.
Dustrol		Yes	Yes	Medium grade road oil. Flammable.
ELO			Yes	---
Formula 125		Yes		Organic cementing agent and a sodium methyl siliconate base. Effective in gravel to clay. Caustic in concentrated form. Approximate cost $10/gal.
Gelatin 15XPF		Yes		Good penetration in sand. Forms hard, brittle surface.
Goodyear X335			Yes	---
Heavetex P1396	Yes			---
Heavetex P1397	Yes			---
Hysol	Yes			---
K-aton 101			Yes	---
Landlock			Yes	---
Lemac 40			Yes	---
Orzan GL-50		Yes		Cementing material that can be sprayed or mixed with soil. Approximate cost $0.30/gal.
Pacific N 748 N	Yes		Yes	---

(Continued)

TABLE 10 (continued)

Category and Agent	Attribute*			Comments**
	Strength	Water	Dust/Wind	
Miscellaneous materials (continued)				
Stabinol		Yes		3:1 mix of Portland cement and Resin 321 or a complex salt. Deteriorates after long storage.
Sulfite liquor	Yes			Effective sprayed on sand and gravel. Easily leached out by water.
Terra-krete No. 2		Yes		Inorganic and organic materials with a synthetic binder. Approximate cost $2.50/gal.
Tung oil		Yes		---
Waste oil	Yes	Yes	Yes	---

---

* Attributes are marked yes where addition to soil is claimed (not necessarily substantiated) to stabilize generally, to repell water or resist water erosion, or to resist dusting or wind erosion. Dispersants are another group of additives used primarily to aid in the compacting process; they are not included in this table but are discussed in the text.

** The pollution potential of additives should be given special consideration prior to usage.

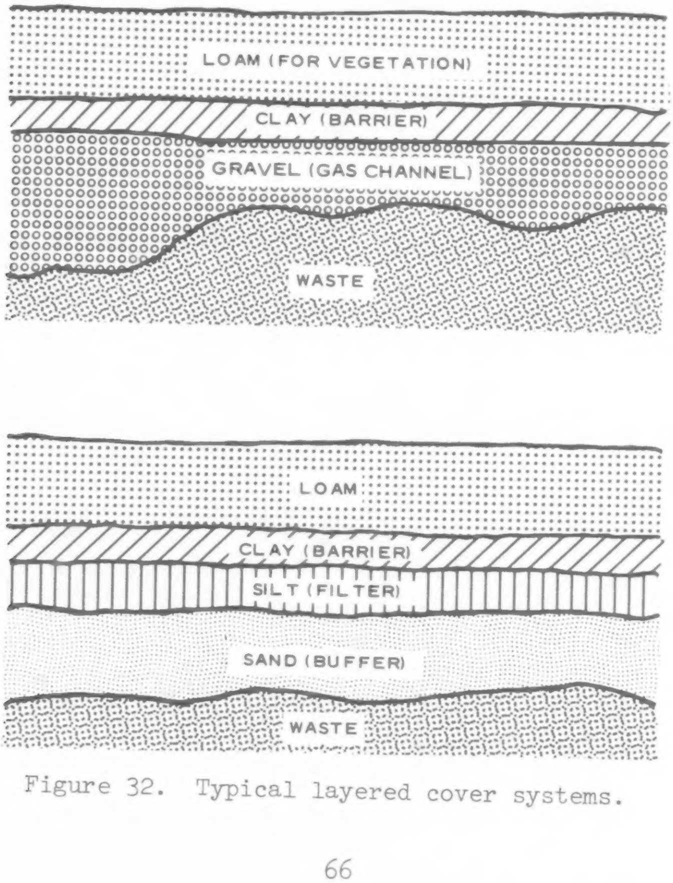
LOAM (FOR VEGETATION)
CLAY (BARRIER)
GRAVEL (GAS CHANNEL)
WASTE
LOAM
CLAY (BARRIER)
SILT (FILTER)
SAND (BUFFER)
WASTE

Figure 32. Typical layered cover systems.

Buffer Layer

A buffer layer may be described as a random layer having a subordinate covering function and characteristics in comparison with the adjacent layer. The principal service of a buffer is to protect a barrier layer or membrane located above or below. The buffer shields a vulnerable, thinner barrier or sheet from tears, cracks, offsets, and punctures. Below a barrier, the buffer layer also provides a smooth, regular base. Any soil type will serve as a buffer ordinarily, but it should be free of clods. A properly placed buffer filling voids around barrels of waste serves to prevent settlement and disruption of the final capping cover.

Water Drainage Layer or Channel

A water drainage layer, blanket, or channel may be designed into the cover in numerous ways to provide a path for water to exit rapidly. Poorly graded sand and gravel are recommended as effective drainage materials, i.e., soils classified GP and SP. Drainage channels and layers may be associated with a system of buried pipe drains, but the expense of this combined system ordinarily limits its applicability to high-priority disposal areas. Some experience has suggested that biological buildups or icing can seriously interfere with operation of drainage layers.

Filter

Where layers with grossly discordant grain sizes are joined, there may be a tendency for fine particles to penetrate the coarser layer. As a result, the effectiveness of the coarse layer for water drainage may be reduced by clogging of pores. Removals from the fine layer may promote additional bad effects, such as internal erosion and settlement (see Dispersants). Similar problems can develop around pipe drains buried in the cover system.

Such problems are commonly confronted in construction and agriculture, and procedures have been established for choosing grain size for a filter. A widely used criterion[35] is written

$$\frac{D_{15}(\text{filter})}{D_{85}(\text{base})} < 4 \text{ to } 5 \qquad (6)$$

where D_{15} and D_{85} refer to the grain sizes for which 15 and 85 percent by weight of the soils are finer, respectively. A review of filter construction is available elsewhere.[36] Less rigorously, filters might ordinarily be specified as SP, SM, ML, and MH soils depending on the classification of soil to be protected. A filter fabric or cloth with k comparable to that of sand may be considered in place of a filter layer to protect sand and gravel.

Gas Drainage Layer and Vents

A gas drainage layer has consistency and configuration similar to those of the water drainage layer or channel. Both layer types function to transmit preferentially. The position in the cover system is the main distinction.

The gas drainage layer is placed on the lower side to intercept gases rising from waste cells, whereas the drain for water is positioned on the upper side to intercept water percolating from the surface.

Gas vents are a proven tool in the present state of the art in municipal waste landfilling. It has been found that dangerous concentrations of flammable gases can accumulate if not vented properly to the atmosphere. Figure 33 illustrates two recommended gas vents. The designer should be aware of the fact that occasionally a biological or ice buildup can interfere with proper channeling or venting.

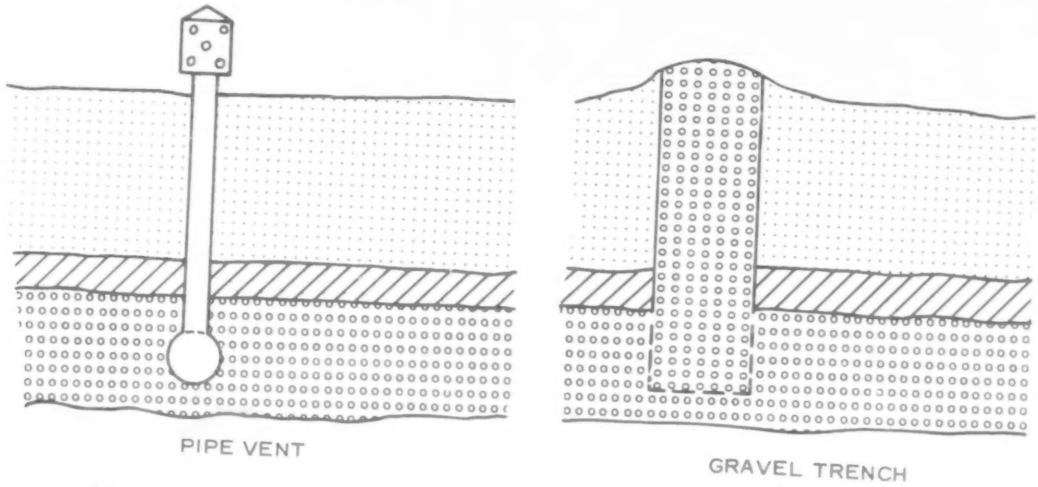

Figure 33. Two types of gas vents for layered cover systems.

Construction Techniques

Some general recommendations for layering the final or closure cover from the bottom up are as follows:

a. Make buffer layer below barrier thick and dense enough to provide a smooth, stable base for compacting in c below.

b. Compact all layers except topsoil and top lift of upper buffer.

c. In barrier layer, strive for 90 percent of maximum density according to 5- or 15-blow compaction test.

d. Cover barrier layer soon enough to prevent much drying.

e. Provide sufficient design thickness to assure performance of layer function; specifying a 6- to 12-in. minimum should prevent excessively thin spots resulting from poor spreading techniques.

f. Construct in units small enough to allow rapid completion.

g. Consider seeding topsoil at time of spreading.

SECTION 6

NONSOIL COVER MATERIALS

Two broad, contrasting classes of nonsoil cover materials are described in this section. Commercially available capping materials or membranes may be preferable to soil-based systems over industrial wastes that pose a high risk of serious pollution (where not properly shielded). In contrast elsewhere, an economic advantage may accrue from using inexpensive, locally generated wastes in place of scarce, indigenous soil.

COMMERCIAL MATERIALS

For high assurance or factor of safety for performing specific functions, available commercial materials should also be considered. For example, bituminous and portland cement concrete barriers and membranes of various types function alone or in conjunction with soil or granular waste layers to exclude water. A summary of materials and their characteristics is presented in Table 11. Of course, the cost of buying and installing these special systems is prohibitive for most solid waste covering (Table 12).

General Considerations

Important characteristics of flexible membranes and rigid barriers include vulnerability to tearing or cracking, respectively. A smooth buffer of sand should reduce membrane puncture during construction, but extra long-term planning will be necessary against stressing effects of differential settlement. The rigid barriers sometimes have an advantage because cracks can be exposed, cleaned, and repaired (sealed with tar) with relative ease.

Deterioration is another major problem for serious consideration. Concrete barriers are susceptible to chemical deterioration in harsh environments such as those rich in sulfates. Sunlight, burrowing animals, and plant roots increase the deterioration of membranes. Twenty years is about the extent of experience with membranes.[37] Longer design service life may be somewhat risky in adverse environments and conditions.

The cost of commercial coverings will often be the overriding consideration. Table 12 provides figures that the designer may use as first approximations of installed cost. These data are from a few summary sources, mostly concerned with irrigation canal linings, and no assurance is offered that all figures are mutually concordant and directly applicable to relatively small waste covering operations. The designer will need to analyze the cost effectiveness based on specific needs and local material and labor costs.

TABLE 11. PRODUCTS RECOMMENDED FOR HIGH-PRIORITY COVER

Material and Description	Advantages	Disadvantages
Bitumen cements or concretes (AC-40 and AC-20 viscosity grades.)	a. Provide tight, impervious barriers covering municipal/hazardous waste. b. Good availability. c. May be used as thick waterproofing layers in flat areas or on slopes.	a. Expensive b. Special heating and storage equipment required for handling. c. Vulnerable to breaking.
Portland cements or concretes (3000 psi and 5000 psi)	a. Good availability. b. Provides good highly impermeable containers or covers for hazardous waste disposal. Very low water permeability.	a. May crack during curing, allowing potential paths for escaping gases or infiltrating water. b. Leakage from hazardous wastes in liquid form may weaken concrete with time.
Liquid and emulsified asphalts (RC and MC 30, 70, 250, 800, and 3000 liquid asphalts. RS's and CRS's 1 and 2, MS's and CMS's 2, and SS1 emulsion.)	a. Can be sprayed on soil covers to decrease water and gas permeability. b. Can be mixed with soil to form waterproof layer. c. Penetrate open surfaces, plug voids, then cure. d. Penetrate tight surfaces, plug voids, then cure. e. Provide hard, tight, stable membrane (RC and MC 800 and 3000).	a. Must leave sprayed surface exposed until it either cures (RC's, MC's) or sets (SS's). b. Must be covered for protection. c. Require additional equipment to handle and apply the asphalts. Spraying temperatures range from 75° to 270°F (25° to 130°C). d. Use of RC and MC 800 and 3000 in thick membrane construction may require numerous applications.
Tars (RT 1, 2, 3, 4, 7, 8, and 9. RTCB 5 and 6).	a. Can be sprayed on soil surfaces or mixed with particles. Tars mix well with wet aggregate. b. Penetrate tightly bonded soil surfaces and plug voids (RT 1 and 2). c. Penetrate loosely bonded fine aggregate surfaces and plug voids (RT 2, 3, and 4). d. Penetrate loosely bonded coarse aggregate surfaces and plug voids (RT 3 and 4). e. Low spray on temperatures 60° to 150°F (15° to 65°C) for RT 1, 2, 3, and 4 and RTCB 5 and 6. f. Provide hard, tight, stable surface membrane (RT 7, 8, and 9). May be used in flat areas or on slopes. g. Provide good penetration, then cure to form hard surface (RTCB 5 and 6).	a. Tar may be removed by traffic if not covered with a protective soil layer. b. Tars are more susceptible to weathering effects than asphalts. Must be protected from weathering. c. Require special equipment for handling and application. d. RT 7, 8, and 9 require application temperatures of 150° to 225°F (65° to 105° C).
Bituminous fabrics	a. Require minimal special equipment and skill. b. Resist tearing.	a. Expensive. b. Laps should be sealed.
Commercial polymeric membranes (Butyl rubber)	a. Available in various size sheets. b. Can be reinforced with fibers for added strength. c. Can be joined at seams to cover large areas. d. Good availability. e. Good heat resistance. f. Very low water permeability. g. Low vapor transmissivity.	a. Poor resistance to weathering and abrasion. b. May be damaged by gnawing/burrowing animals if not protected with soil. c. May be damaged by heavy equipment operating directly on surface and may be punctured by large stones or sharp edges in direct contact.

(continued)

TABLE 11 (continued)

Material and Description	Advantages	Disadvantages
Commercial polymeric membranes (continued)		
(Neoprene rubber (chloroprene rubber))	a. Good resistance to oils, grease, gasoline, acids, and alkalies. b. Good resistance to abrasion, weathering, and flexing. c. Can be joined at seams to cover large areas. d. Can be reinforced with fibers for added strength. e. Very low water permeability.	a. More expensive than other natural and synthetic rubbers. b. Use is limited to special applications because of _a_ above. c. May be damaged by gnawing/burrowing animals if not protected with a soil layer. d. May be damaged by heavy equipment operating directly on surface and may be punctured by large stones or sharp edges in direct contact.
(Hypalon (chlorinated chlorosulfinated polyethylene))	a. Outstanding resistance to abrasion and weathering. b. Available in various size sheets. c. Can be fiber reinforced for added strength. d. Can be joined at seams to cover large areas. This can be done onsite or at factory. e. Very low water permeability.	a. May be damaged by gnawing/burrowing animals if not protected with a soil layer. b. Does not perform satisfactorily when exposed to amyl acetate, benzene, carbon tetrachloride, cresote oil, cyclohexane, dioctyl phthalate, ethyl acetate, lacquer methylene chloride, napthalene, nitrobenezene, oleum, toluene, tributyl phosphate, trichloroethylene, turpentine, and xylene. c. For good seam quality, the weather must be at least 50°F (10°C) and sunny. If not, heat has to be applied to seams to develop full early strength. d. May be damaged by heavy equipment operating directly on membrane. e. May be punctured by large stones or sharp edges in direct contact.
(Polyolefin (polyethylene and chlorinated polyethylene))	a. Available in various sizes. b. Can be joined at seams to cover large areas. c. Can be fiber reinforced. d. Chlorinated polyethylene has excellent outdoor durability. e. Very low water permeability.	a. May be damaged by gnawing/burrowing animals if not protected with a soil layer. b. May be damaged by heavy equipment operating directly on membrane. c. May be punctured by large stones or sharp edges in direct contact. d. Polyethylene has poor durability when exposed.
(Elasticized polyolefin (3110))	a. Can be joined at seams to cover large areas. Field bonding of individual sheets is done using a heat seaming technique. b. Excellent resistance to soil microorganisms, extremes of weather, and ozone attack. c. Very low water permeability.	a. May be damaged by gnawing/burrowing animals if not protected with a soil layer. b. May be damaged by heavy equipment operating directly on membrane. c. May be punctured by large stones or sharp edges in direct contact with membrane.

(continued)

TABLE 11 (continued)

Material and Description	Advantages	Disadvantages
Commercial polymeric membranes (continued)		
(PVC (polyvinyl chloride))	a. Fair outdoor durability. b. Available in sheets of various sizes. Factory seaming available. c. Seams can be bonded in the field with vinyl to vinyl adhesive. d. Generally used without reinforcement, however, can be fiber reinforced for special applications. e. Very low water permeability. f. Less permeable to gas than polyethylene.	a. May be damaged by gnawing/burrowing animals if not protected with a soil layer. b. For extended life, this membrane must be covered with soil or other material. c. May be damaged by heavy equipment operating directly on surface and may be punctured by large stones or sharp edges in direct contact. d. Not as durable as hypalon or chlorinated polyethylene. e. Becomes stiff in cold weather.
(EPDM (ethylene-propylene-unsaturated diene terpolymer))	a. Good outdoor durability. Ozone and oxidation resistant. b. Sheets may be bonded to cover large areas. c. Very low water permeability.	a. May be damaged by gnawing/burrowing animals if not protected with a soil layer. b. May be damaged by heavy equipment operating directly on surface and may be punctured by large stones or sharp edges in direct contact.
Surfur (thermoplastic coating) (Molten sulfur)	a. Can be formulated for a wide range of viscosities. b. Can be sprayed on various materials to act as a bonding agent. c. Reduces permeability. d. Resistant to weather extremes (subfreezing to very hot). e. Resistant to acids and salts. f. Can be mixed with fine aggregate to form a type of concrete.	a. Requires high temperatures for workability, 250°-300°F (20°-150°C). b. Requires special equipment for handling and application. c. May not tolerate much shear deformation. d. If applied to hazardous waste containers prior to land disposal, heat absorption by volatile wastes may cause gas expansion and possible explosion hazards.
Bentonite	a. No special equipment needed. b. Can be mixed with soil.	a. Difficult to handle and spread after wetting. b. Susceptible to shrink-swell.

TABLE 12. ESTIMATED UNIT COSTS* FOR SOME COVER LAYERS

Layer Type and Thickness	Installed Cost dollars/yd^2
Loose soil (2 ft)	0.35
Compacted soil (2 ft)	0.70
Cement concrete (4 in.)	9.00
Asphalt concrete (4 in.)	2.50-3.50
Soil-cement (7 in.)	1.50
Soil-asphalt	1.50
Polyethylene membrane (10 mil)†	1.00-1.50
Polyvinyl chloride membrane (20 mil)	1.30-2.00
Chlorinated polyethylene membrane (20-30 mil)	2.40-3.20
Hypalon membrane (20 mil)	2.50
Neoprene membrane	5.00
Ethylene propylene rubber membrane	2.70-3.50
Butyl rubber membrane	2.70-3.80
Paving asphalt (2 in.)	1.20-1.70
Sprayed asphalt membrane (1/4 in.) and soil cover	1.25-1.75
Reinforced asphalt membrane (100 mil) and soil cover	1.50-2.00
Bentonite layer (2 in.)	1.40
Bentonite admixture (9 lb/yd^2) in soil	0.75

* Based on data assembled in References 20, 37, 38, 39, and 40 with qualitative adjustments to present.

† Not recommended because of thinness.

Portland Cement Concrete or Mortar

Portland cement concrete or mortar ordinarily should be placed on a well-compacted base. This requirement and the high cost (Table 12) make concrete (and mortar to a lesser degree) unattractive for use over municipal and other soft solid waste that will settle subsequently. Reinforcing steel bars do not materially improve the integrity except to reduce separation after cracking, and steel increases cost by about 15 percent.[38]

The water-cement mixing ratio should not exceed 0.65 in mild climates. This limit should be reduced to 0.5 in severe climates where freeze-thaw is frequent, but as a general rule, placement of cement concrete or mortar should be restricted to the warm season. Portland cement, sand, and gravel should be proportioned approximately 17, 39, and 44 weight percent, respectively, in concrete. In large operations consideration might be directed to applying cement mortar pneumatically as shotcrete; unit cost should be about half that for concrete. Concreting plans and specifications should include a paragraph on curing, since curing greatly improves durability and water tightness. Ordinarily, keep the concrete or mortar saturated for at least 5 days; a wet soil cover will prolong curing advantageously. A design life of 50 years would be reasonable except for the early development of fractures from differential settlement.

Bituminous Concrete or Mortar

Besides its rather substantial advantage in unit cost (Table 12), bituminous concrete or mortar can be placed in freezing weather and can use somewhat poorer quality aggregate than cement concrete. Asphalt usually constitutes about 7-10 percent of the mixture. Solids should be well graded from gravel down to about 10 percent passing the No. 200 sieve for concrete. Asphalt mortar uses only sand and is sometimes applied pneumatically. Special hot-mixing equipment may be available on contract or from road agencies, especially in the off season. Compaction is essential, yet flexing in the process (see Lift Thickness under COMPACTION) can easily cause unacceptable cracking. Thickening the buffer soil below helps reduce the cracking problem. A soil sterilant will discourage vegetation from penetrating the concrete at a later time.

Bituminous materials are considered potentially useful for encapsulating radioactive wastes,[37] where the design life should exceed 40 years. Experience with more conventional uses of bituminous concrete (as in canal linings) suggests that the soil covering is almost essential as protection and will extend the life well beyond the 10-20 years expected[20] otherwise. Unfortunately, soil cover complicates maintenance, and it may be prudent to consider delaying the final cover application until most settlement has taken place. A particularly attractive dual usage of an asphalt concrete barrier is where it serves also as a surface pavement, e.g., a parking lot.

Bitumen-sulfur Concrete

Substitution of sulfur for asphalt in bituminous concrete offers promise for reasons of economy and environmental responsiveness. Sulfur can replace 25-50 percent of the asphalt with little sacrifice of desired properties.[41] The usual equipment for preparation and handling of asphaltic concrete works as well on the sulfur-extended material.

Sprayed Bituminous Membranes

Membranes formed in place with cutback, emulsified, or airblown asphalt are common for canal lining and show promise for special solid waste covering. A high-softening-point asphalt blown hot with a phosphoric catalyst is best.[20] Membrane thickness should be about 1/4 in. Special equipment needed for spraying the membrane may be available from highway or street maintenance shops in the off-season. Soil buffers above and below are necessary to reduce vulnerability to puncture or deterioration; the lower should be sprayed with water to prevent excessive dust and attendant pinholes, etc. A soil sterilant discourages vegetation from germinating and penetrating the membrane.

With special equipment, one part of shredded rubber can be mixed with three parts of asphalt and spread to form a membrane with superior flexibility and tensile strength, besides consuming large quantities of solid waste scrap tires.[42] The rubber reacts with the resin portion of the asphalt with attendant swelling. Thus, the membrane is especially effective for sealing.

Reinforced Bituminous Membrane

The sprayed in-place technique can be extended by incorporation of a fabric for added strength; polypropylene has been used.[39] After the fabric has been joined into a continuous sheet, the sealant of anionic asphalt emulsion with fibers, water, and wetting agent is sprayed on.

Sprayed Sulfur Membrane

Sprayed sulfur membranes appear to offer promise in place of asphalt or cement in chemically severe environments. Summary information on this relatively new development is given in Table 11 and Reference 43.

Polyurethane Foam

The use of polyurethane foam for both lining and covering landfills has been promoted.[44] A final soil cover is applied over the foam.

Prefabricated Bituminous Membrane

This category of membranes comprises all thin bitumen-coated felts or fiber-mats, similar to those used in the roofing industry.[20] Reinforcing materials used are jute, hemp, and glass fiber. The membranes have a thickness of approximately 1/4 in. and are supplied in rolls.

Construction procedures similar to those used for hot sprayed membranes should be followed in preparing the subgrade and placing the membrane. All joints of the membrane are usually lapped at least 2 in. and bonded with hot asphalt cement, cold mastic, or special cutback.

Plastic and Rubber Membranes

Extensive use is being made of plastic and synthetic rubber membranes for lining ponds and pits but, as yet, only sparse use in solid waste cover systems.[44,45] The most common are plasticized polyvinyl chloride, polyethylene, and butyl rubber. Considering both performance and cost, polyethylene may be the most economical.[20]

Membranes are supplied in pieces up to 100 ft wide to minimize the amount of field joining required, but joining does not require highly trained labor. Polyethylene and butyl are supplied in folded rolls while polyvinyl chloride is generally accordion-folded in both directions so that the sheet can be opened lengthwise from the back of a truck. Adjacent sheets need to be sealed, not just overlapped, to produce watertightness. Strips 10 by 1000 ft were unrolled in one case[45] in Delaware to cover 10 acres of landfill; shingled overlaps were left unsealed.

Polyvinyl chloride sheets can be joined and sealed by injecting a small amount of adhesive along a 4-in. overlap, then gently smoothing the adhesive-covered area to effect a bond. A few minutes later the large sheets can be opened. Special adhesives that develop strength more slowly are used with polyethylene and butyl. Tape can be used to join panels of polyethylene also.

Plastic and synthetic rubber membranes should be covered with soil as soon as possible to prevent early deterioration by mechanical damage (particularly wind damage) and sun exposure. To prevent excessive softening and dimensional changes in hot climates, placement may have to be limited to nighttime (for polyethylene and polyvinyl chloride).

Bentonite

Bentonite is a versatile material that warrants serious consideration on special waste-covering jobs. The primary constituent is the clay mineral montmorillonite. Bentonite is distinguished from other clays by its extreme fineness, high absorbency, and property of swelling in water. High-quality bentonite contains up to 90 percent colloidal-size particles. The best quality bentonite comes from Wyoming, but local bentonite may be a satisfactory, cheaper substitute.

Bentonites exhibit high swelling or low swelling according to whether the principal cation is sodium or calcium. High-swelling sodium bentonite, when unconfined, absorbs nearly 5 times its weight of water and at full saturation is nearly 15 times its dry bulk. On drying, it shrinks to its original volume. The swelling-shrinking cycle can be repeated over and over, and this behavior gives bentonite its water-sealing power. Low-swelling calcium bentonite free-swells 1.5 to 7 times in water.

The Soil Conservation Service (SCS) standards for sealing farm ponds with bentonite[39] approximate the requirements for soil cover over solid waste as follows:

Soil	Application Method	Application Rate lb/ft^2
Clay	Pure membrane or mixed layer	1.0-1.5
Sandy silt	Mixed layer	1.0-1.5
Silty sand	Mixed layer	1.5-2.0
Clean sand	Mixed layer	2.0-2.5
Open rock or gravel	Clay or sand mixed layer	2.5-3.0

WASTE MATERIALS

The other category of nonsoil materials that is available for covering solid waste ranges through a long and diverse list of granular wastes (some are in fact soils). The designer should review those presented below for direct applicability and to suggest other possibilities in his vicinity.

Fly Ash*

The idea of effectively covering waste with another waste makes fly ash a promising candidate for consideration. In a few places (e.g., West Virginia), fly ash is already being used as intermediate cover. Sources circled in Figure 34 account for much of nearly 40 million tons of fly ash produced

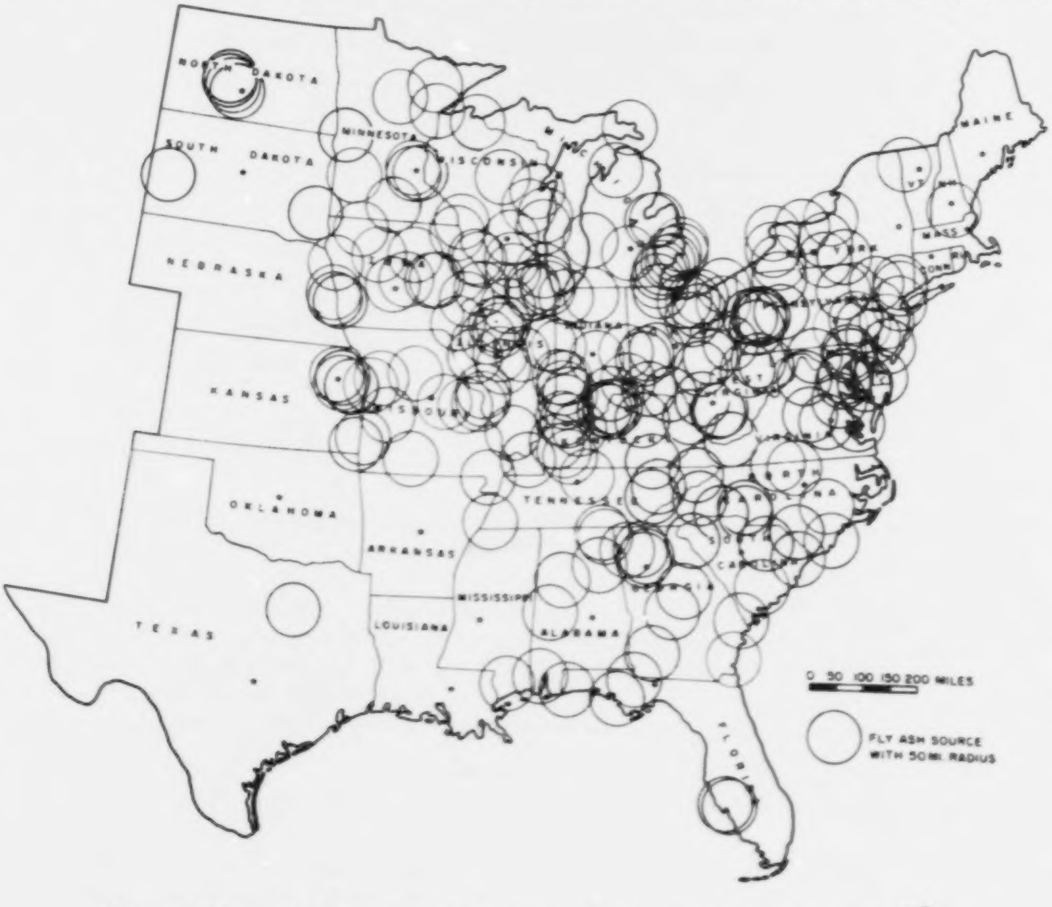
NORTH DAKOTA
SOUTH DAKOTA
MINNESOTA
WISCONSIN
NEBRASKA
KANSAS
MISSOURI
OKLAHOMA
ARKANSAS
TEXAS
LOUISIANA
MISSISSIPPI
ALABAMA
TENNESSEE
NORTH CAROLINA
SOUTH CAROLINA
GEORGIA
FLORIDA
MAINE
VT
NH
MASS
CONN
0 50 100 150 200 MILES
FLY ASH SOURCE WITH 50 MI. RADIUS

Figure 34. Fly ash sources east of the Rocky Mountains.[28]

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[*] The pollution potential of fly ash has not been entirely defined, and its use in cover at a landfill should be prefaced on favorable conclusions of environmental impact studies.

annually in the United States (more than 85 percent east of the Mississippi River). Other generalities and the use of fly ash in combination with soil are discussed under ADDITIVES AND CEMENTS in Section 5.

Fly ash is essentially a silt with active or latent pozzolanic quality. Figure 35 summarizes grain-size distribution. Coefficient of permeability is about 10^{-4} cm/sec when loose (Figure 21); compaction and cementation can reduce k to as little as 10^{-6} cm/sec, provided no cracks develop. Fly ash is largely nonplastic according to Atterberg limits. The pollution potential from soluble calcium, sulfur, and trace element constituents should be held relatively immobile by the inherently low permeability of properly compacted and reacted fly ash. Fly ash is susceptible to wind and water erosion so that special stabilization, such as with water or waterborne additives, may be necessary.

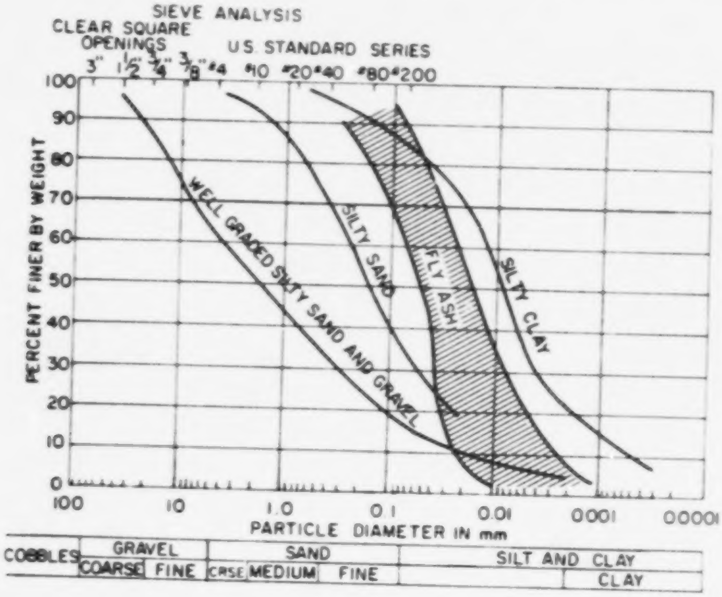


Figure 35. Grain-size distributions for fly ash.[46]

Modified Fly Ash

The principal modification of fly ash is the addition of lime to enhance cementation. The increase in strength should be twofold or more. Where the free lime content of the fly ash is low (as from many eastern coals[30]), lime additions may be necessary to achieve any cementation at all. However, both quicklime and hydrated lime are expensive commercial chemicals, and the need should be clearly established by testing. Hydrated lime is preferred to quicklime for its finer grain size for better distribution. The common mix ratio is 1:4 lime to fly ash, but much less lime should suffice over solid waste where high strength is not usually needed.

The addition of calcium sulfates or calcium sulfite to the fly ash-lime combination serves three purposes. The sulfate speeds up the strengthening/curing process, and its usage provides an outlet for stocks accumulating as waste from gas scrubbers and numerous industrial processes.[32] Additionally, the lime requirements are reduced, typically to about 5 percent in combination with about 15 percent sulfate waste and 85 percent fly ash. Permeability tends to be around 5 × 10^{-6} cm/sec after proper compaction.

Bottom Ash and Slag

Ash and slag at the bottom of the boiler are the counterparts of fly ash carried up the stack. As such, these wastes accumulate to the extent of about 18 million tons annually in the United States and form a significant source of solid waste cover. The source locations are about the same as those in Figure 34. Grain size (Figure 36) is noticably coarser than for fly ash.

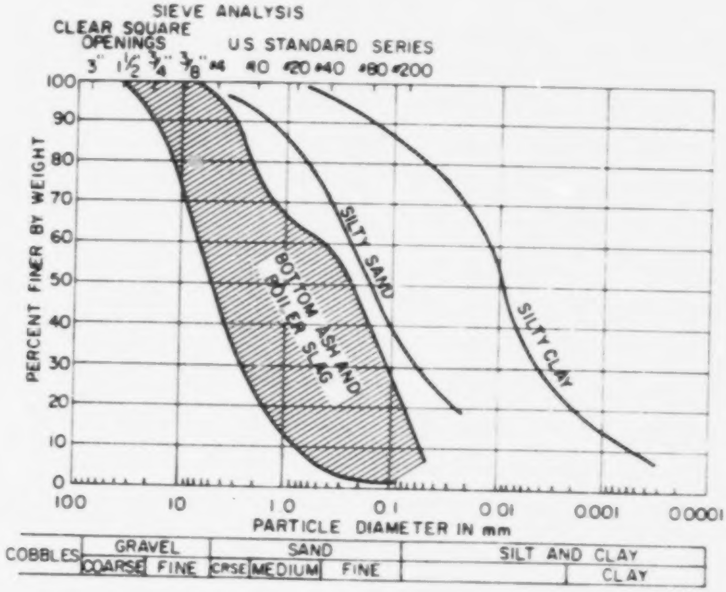


Figure 36. Grain-size distributions for bottom ash and boiler slag.[46]

Permeability (Figure 21) is correspondingly higher (5 × 10^{-3} cm/sec), and these wastes alone are most suitable for granular drainage layers of layered covers. Blending may be required for general suitability as cover.

Furnace Slag

More than 50 million tons of furnace slag are generated each year in the United States in producing iron and steel. These materials are used extensively for road fill and base near sources in the eastern Midwest and elsewhere. The grain size is gravelly and coarser so that the ordinary function for reducing infiltration is totally out. Slag should be considered for aggregate or to blend with other cover materials or for local slope erosion protection. Another possibility is as a thick buffer base which, by its high density, surcharges the waste below and hastens the long-term compaction. Furnace slag is a glass that is sometimes unstable; therefore, the pollution potential of slag deserves special attention. Considerable experience on the pollution potential should be available in slag-producing regions.

Incinerator Residue

Approximately 20 percent of solid waste input volume remains as residue after incineration[47] and should be considered as a possible cover material, particularly in large urban areas. Certain soluble constituents might make this sandy (permeable) waste susceptible to leaching and unsatisfactory as cover where subjected to much percolation. The grain size of one example is given in Figure 37 for comparison with bottom ash/boiler slag in Figure 36.

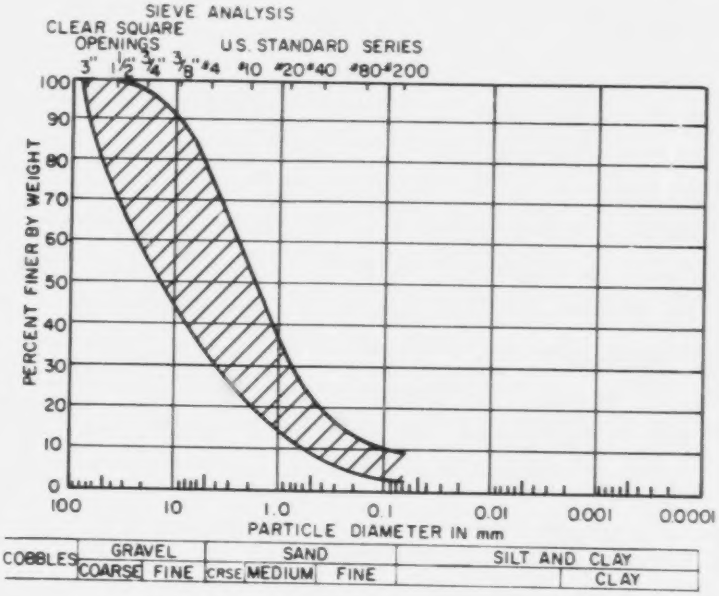


Figure 37. Grain-size distribution for typical incinerator residue from municipal solid waste.

Foundry Sand

Foundry sand is an example of miscellaneous, granular wastes locally available in small tonnages.

Mine and Pit Wastes

Wastes from mining (including overburden at quarries and gravel pits) are in a sense complementary to fly ash as cover material since many mine wastes are preferentially situated away from large urban areas where fly ash is usually abundant. The immense tonnages (see Section 1) of these wastes suggest great potential locally as cover in place of indigenous soil. Disposal sites for neighboring communities can be located near the source mines to reduce cover transportation costs to a minimum. However, siting within the mined-out area is receiving critical scrutiny presently because of the risk of embedment in the permanent water zone. The grain size of mine waste varies widely; rock pieces are usually abundant, but clay may be scarce in fresh mine waste. Such mine waste is ideal for mixing into municipal waste for increased density. On the other hand, mine waste may not serve well as a water barrier and will probably require final covering eventually itself. A review of materials and sources is available in Reference 48.

Mine Mill Tailings

The wastes remaining after hydraulic processing of mined rocks and soils accumulate along with the mine and pit wastes, but at fewer sources. Grain size is in contrast since the distribution is much narrower. Processing of phosphate rock leaves a clay slurry, while many metalliferous ores produce silt-size tailings. Coal-washing plants release a slurry with particle sizes reflective of the original rock grain sizes--clay from shale, sand from sandstone. The pollution potential of slurries retaining traces of organic and inorganic chemicals, such as flotation agents from the separation process, should be considered. A comparison should be made of costs and logistics of handling partially dry slurry versus drying apart and then handling.

Plant Sludges

A precedent is said to have been established already for using innoxious industrial sludge (e.g., paper-mill sludge[11]) over municipal waste. Ordinarily, however, these sludges contain high water contents, and an intermediate drying stage may be necessary before application.

Reservoir and Channel Silt

Water storage reservoirs on rivers and streams begin accumulating sand, silt, and clay even before the impoundment structure is completed. Since these accumulations eventually shorten the effective life of the reservoir, removal for use in covering waste will be doubly beneficial. Similarly, silt is sometimes conveniently available during cleanup of flood protection channels. This potential source has the advantage of providing material in a damp condition rather than a mud. Silt from the Bonne Carre spillway is used extensively around New Orleans for fill, including cover over solid waste.

Dredged Material

The material dredged each year (about 300 million yd^3) by the Corps of Engineers[49] in maintaining waterways and harbors constitutes another large potential stock of cover material. The geographical distribution of available dredged materials favors areas along coasts (Figure 38) and flanking navigable rivers exclusively; but in fact, these favored areas encompass a significantly large part of our solid waste sources also. Besides, these

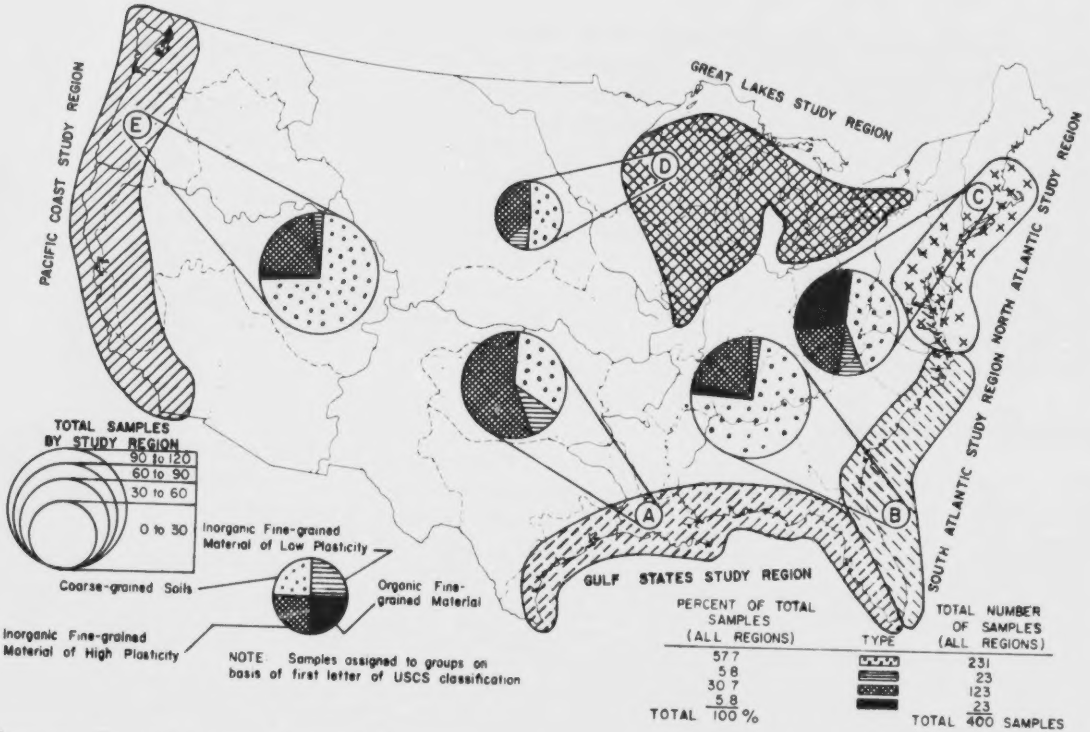

PACIFIC COAST STUDY REGION
GREAT LAKES STUDY REGION
NORTH ATLANTIC STUDY REGION
SOUTH ATLANTIC STUDY REGION
GULF STATES STUDY REGION
A
B
C
D
E
TOTAL SAMPLES BY STUDY REGION
90 to 120
60 to 90
30 to 60
0 to 30
Inorganic Fine-grained Material of Low Plasticity
Coarse-grained Soils
Organic Fine-grained Material
Inorganic Fine-grained Material of High Plasticity
NOTE Samples assigned to groups on basis of first letter of USCS classification
PERCENT OF TOTAL SAMPLES (ALL REGIONS)
TYPE
TOTAL NUMBER OF SAMPLES (ALL REGIONS)
57.7
5.8
30.7
5.8
TOTAL 100 %
231
23
123
23
TOTAL 400 SAMPLES

Figure 38. Types of dredged material, by region, as sampled in Reference 50.

areas tend to provide few other soil sources.

Dredged materials vary greatly in character (Figure 38) from site to site.[50] Figure 39 reveals this variability in terms of USCS types among

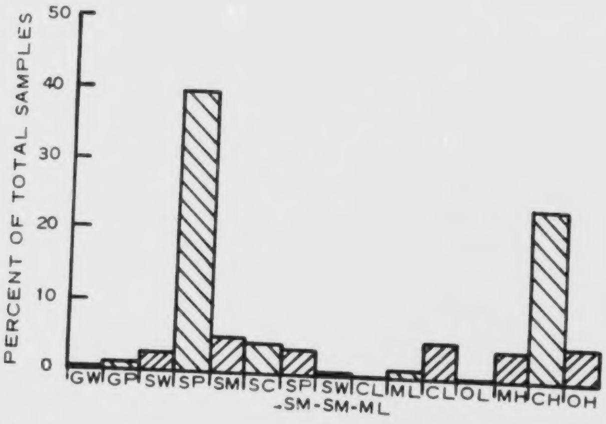


Figure 39. Frequency of USCS types among 400 samples of dredged soils.[50]

400 samples from throughout the conterminous United States. However, there are concentrations in SP and CH types.

One concept considered feasible and perhaps even best for handling dredged material is to reuse the primary disposal site as a holding basin over and over. Accordingly, the dredged material is allowed to consolidate and dry but then is loaded out on trucks and moved to places where it can be put to most productive use. Such a handling system should be ideal for supplying abundant cover material to solid waste disposal sites situated nearby. Unfortunately, drainage of thick accumulations may not lower water content sufficiently,[51] and evaporative drying in thin lifts may be necessary at greater costs.

Composted Sewage Sludge

Sewage becomes a valuable special cover material when the sludge is converted to a convenient, safe form by composting. Several composting processes and combinations are available; one involves forced aeration of piles of digested sludge and bulking material like wood chips.[52] Composting can eliminate malodors and human pathogens and produces a stable, humuslike organic material that is convenient to store and spread. The value of compost is as a source of nutrients for nonfood-chain plants and as an organic amendment to improve the physical properties of soil (i.e., a topsoil conditioner). Advances in this developing field will be prompted by a demand for the compost product; the designer of covers should review periodically his needs in view of changing costs/benefits of compost versus other, more conventional materials for topsoil.

Shale, Soft Rock, and Stiff Clay

Shale, soft rock, and stiff clay are not wastes per se, but in some regions are so abundant as to be the primary prospective sources of fill and waste cover. Large portions of the Great Plains are underlain by shale (see Section 18). These sources are particularly important where the waste burial technique is by trenching, and shale or soft rock is removed in required excavation. Weathered rock usually may be classified as clayey soil, from CH to ML. Relatively unweathered shale is commonly hard and requires ripping (with a special dozer accessory) for excavation. The resultant blocky material is coarse and often has to be spread, trafficked, and dried to reduce adequately the block size. The high field density of the cover of stiff Tertiary clay in Figure 22 reflects the original, high density of lumps and chunks not broken down during cover spreading and compaction.

SECTION 7

SUMMARY OF CONSIDERATIONS FOR OPERATIONS PLAN OR SPECIFICATIONS

The following plan is suggested for development of cover at waste disposal areas and operations according to the aims of Public Law 94-580. The plan is based on the current state of the art (reviewed in Section 1) and the consideration of numerous cover functions (Sections 2 and 8-22).

GENERAL OUTLINE

For the most effective development of a solid waste cover system, the following general steps are considered to be basic. Some leeway may be available in the soil testing program, but the importance of tests should not be underestimated since they provide quantitative characterization of the materials available.

a. Establish cover functions (based on accurate review and projection of waste type, climate, population, hazards, etc. Follow generally the guidance of Section 2).

b. Inventory available cover systems.

   (1) Establish cover soil sources (along with general types and quantities available).

   (2) Classify soils from all significant soil sources (by testing representative samples. Bulk samples should represent mixed material after handling. Assign tests, such as grain-size gradation and Atterberg limits, to classify according to USC and USDA systems).

   (3) Obtain special testing (for strength, compaction, permeability, capillary head, clay mineralogy, etc., according to cover function requirements).

   (4) Review nonsoil options.

c. Choose best cover systems.

   (1) Rank functions by importance.

   (2) Rank available cover for effectiveness in each function.

    (3) Make choice.

  d. Design cover system.

    (1) Design basic placement and configuration for choice c(3).

    (2) Design for other functions not fulfilled by d(1).

  e. Plan operation and prepare specifications.

  f. Establish quality control-assurance.

RECOMMENDATIONS FOR SPECIFIC DESIGN ELEMENTS

The following paragraphs summarize choice of material and design for specific functions:

  a. Impede infiltration/percolation by:

    (1) Increasing surface slope and developing ditch system.

    (2) Mixing well to avoid permeable zones.

    (3) Blending other soils for better gradation.

    (4) Using additives.

    (5) Increasing cover thickness.

    (6) Using barrier membranes.

    (7) Compacting (with special compacting equipment).

    (8) Using a layered system.

  b. Assist infiltration/percolation by:

    (1) Reducing surface slope.

    (2) Using permeable soil.

    (3) Eliminating compaction requirements.

  c. Impede gas movement by:

    (1) Using very fine soil, such as clay.

    (2) Maintaining high degree of saturation.

  d. Assist gas movement by:

    (1) Using coarse granular cover soil, or

    (2) Incorporating venting system.

e. Control water erosion by:

    (1) Using favorable soil (according to the universal soil loss equation (USLE)).

    (2) Specifying coverages and compactive effort.

    (3) Reducing surface slope.

    (4) Providing surface drainage and perimeter ditch.

    (5) Establishing vegetation quickly.

    (6) Providing mulch and other temporary slope protection.

    (7) Using additives.

f. Reduce wind erosion by:

    (1) Choosing coarse soil (according to the wind erosion equation (WEE)).

    (2) Minimizing knoll-like configurations on surface.

    (3) Choosing favorable length, width, and orientation designs.

    (4) Establishing vegetation quickly.

    (5) Using additives.

    (6) Using wind barriers.

g. Minimize dust by:

    (1) Centralizing haul road systems.

    (2) Maintaining haul roads.

    (3) Applying dust palliatives.

    (4) Starting vegetation early.

h. Hold slope stability by:

    (1) Designing according to stability analyses.

    (2) Keeping inclination at 1:4 or less.

    (3) Providing toe drains and slope protection.

(4) Using the trench method in special cases.

(5) Incorporating slope berms.

(6) Using zone construction.

(7) Compacting to prescribed standards.

(8) Providing features for seepage control or drainage.

i. Reduce cold climate effects by:

(1) Using coarse granular soil for cover.

(2) Reserving supply of unfrozen cover material.

(3) Scheduling operations on a seasonal basis.

Some other functions of cover are of a secondary nature, and they are addressed in the outline above by way of the more primary functions. Thus, steps taken to control gas movement will effectively minimize fire hazard. Other functions are largely considered in a qualitative manner in the present state of the art. For example, the controls of animal burrowing and vector emergence have not been studied in detail but are rather confidently addressed in general terms.

The question of steps and provisions in design to be taken in anticipation of future use of the landfill cannot be brought into sharp focus until those future uses are established. Section 22 provides guidance of a general nature. In any case, documentation of the operation and a plan for long-range maintenance and emergency repair seem essential in view of the growing list of forgotten dumps reappearing as serious, expensive problems of restoration.

SECTION 8

CONTROL OF INFILTRATION/PERCOLATION

Percolation is the process whereby water passes through a soil zone or profile such as solid waste cover. Percolation is closely related to but not synonymous with infiltration, which relates to the entry of water into the soil through pores and cracks in the surface. Large openings within the soil allow relatively rapid gravitational infiltration and percolation while smaller pores restrict movement to slower capillary and adsorptive actions.

Most water enters a waste disposal area either as rainfall (or snowmelt) or by man-induced surface circulation. Natural precipitation is addressed in this section although recirculation of leachate may become commonplace in the future as a means of hastening biochemical stabilization.

FACTORS AFFECTING INFILTRATION/PERCOLATION RATES

Figure 40 outlines the factors affecting infiltration;[53] selected factors are discussed below.

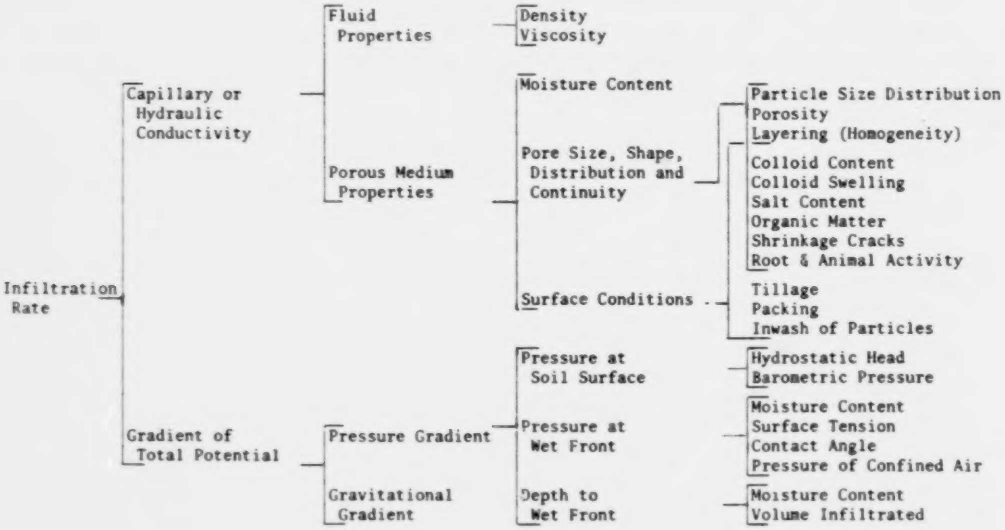

Infiltration Rate
Capillary or Hydraulic Conductivity
Gradient of Total Potential
Fluid Properties
Porous Medium Properties
Pressure Gradient
Gravitational Gradient
Density
Viscosity
Moisture Content
Pore Size, Shape, Distribution and Continuity
Surface Conditions
Pressure at Soil Surface
Pressure at Wet Front
Depth to Wet Front
Particle Size Distribution
Porosity
Layering (Homogeneity)
Colloid Content
Colloid Swelling
Salt Content
Organic Matter
Shrinkage Cracks
Root & Animal Activity
Tillage
Packing
Inwash of Particles
Hydrostatic Head
Barometric Pressure
Moisture Content
Surface Tension
Contact Angle
Pressure of Confined Air
Moisture Content
Volume Infiltrated

Figure 40. Factors affecting the infiltration rate into unfrozen soil.

Idealization of Infiltration Process

Numerous models of the infiltration process have been proposed over the last 50 years. The Horton model is described briefly here as one example of a general infiltration rate-time relationship.[54] The curve in Figure 41 shows the infiltration capacity function during a rainstorm and represents the limit for water entering a soil cover. The maximum infiltration rate occurs at the beginning, and the rate decreases first rapidly and then more slowly before reaching a stable minimum. The minimum infiltration rate usually approaches the percolation rate of the soil.

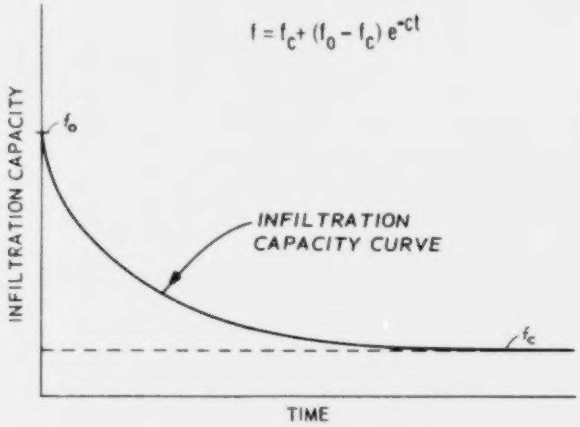


Figure 41. General infiltration rate function.

Refer to Figure 42 for an illustration of the relationship between rainfall intensity and infiltration capacity. Rainfall of intensity (units length/time) below the infiltration capacity penetrates the surface and either contributes to groundwater flow or becomes part of the capillary water content of the soil. Some of this groundwater returns to the atmosphere as vapor through evaporation and transpiration. When the rainfall intensity exceeds the infiltration capacity, water accumulates on the surface and runoff occurs. Therefore, during a rain, as the infiltration capacity of the soil decreases, the amount of runoff increases.

Soil Moisture Content

The most important factor affecting infiltration is usually the moisture content of the soil. The infiltration process is driven[53] by the combined gravity and capillary forces acting downward. Capillary force also diverts water laterally (and even upward) from large pores to capillary pores, which may be very numerous. As the process continues, capillary pores become filled; and with percolation to greater depth, the gravitationally driven water encounters increased resistance due to reduction in large-pore space and sometimes also to a barrier, such as clay. A rapid reduction of

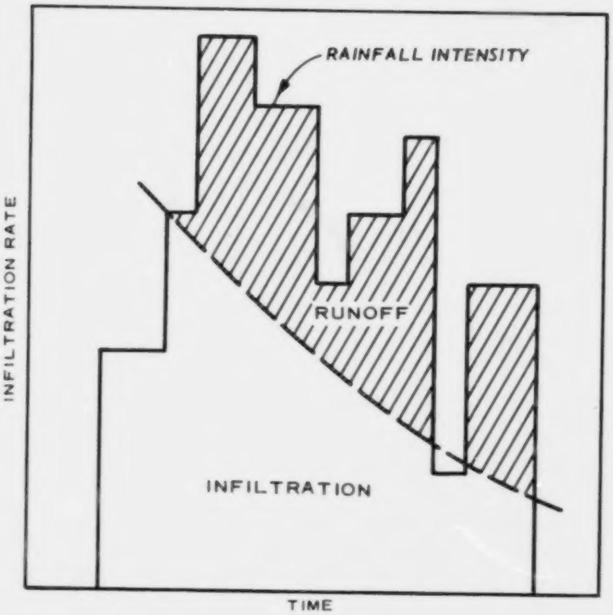


Figure 42. Relationship of rainfall, runoff, and infiltration during a rainfall event.[55]

infiltration rate occurs in the first few hours of a storm (Figure 42). High and low intensities, even within one storm, may be directly reflected in the rates of infiltration and runoff. Periods of low intensity permit recovery, either wholly or partially, of high infiltration rates by providing time for elimination of surface water accumulations and for internal drainage of gravitational water within the soil.

Soil Surface Factors

Falling water drops and overriding traffic may disrupt the structure of bare soil and cause crusting, particularly in natural soils. The crust[56] is the top few millimeters of soil, which differs considerably from that below, and is characterized by few large pores, high bulk density, and platiness and stratification. The crust usually has a low coefficient of permeability, and in effect impedes infiltration.

Susceptibility to crusting is directly related to low organic matter, high exchangeable sodium, and high silt. These components all affect the structural stability of soil aggregates against breakdown by the slaking action of water. Soils high in silt apparently have sufficient particle-to-particle contact to form bonds when the soil dries. Silt also has low shrinkage potential, so that the hard crust does not crack or disintegrate by itself.

Vegetation Factors

Vegetation or other surface cover has considerable influence on infiltration by attenuating rainfall kinetic energy and reducing crusting. Such mulches as straw, burlap, or dead grass are effective attenuators; Figure 43 shows how straw and burlap act to maintain a high infiltration rate. Natural cover of grass, trees, or crops also increases the infiltration rate by providing large root passages for water and by breaching crusts that have formed. An effect of vegetation should always be included in calculating the infiltration rate (see DETERMINING INFILTRATION).

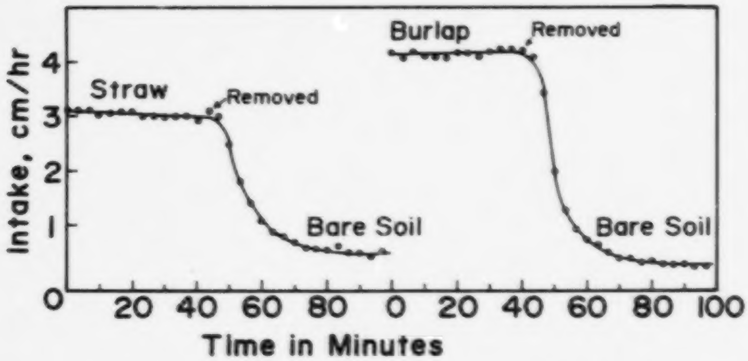


Figure 43. Effect of mulches on infiltration rate (from Miller and Gifford in Reference 56).

Frozen Condition

Freezing of pore water can reduce infiltration severely (see discussion under DETERMINING INFILTRATION).

Flow in Unsaturated Soils

The processes of infiltration and percolation in solid waste cover soil seldom involve full saturation such as discussed under PERMEABILITY TESTS in Section 3. Partial saturation complicates flow (Figure 44), but the fundamental concepts remain valid. Various investigators[57] have shown that water flows through unsaturated soil according to a modified form of Darcy's law in which k is a nonlinear function of water content, i.e., $k(\theta)$.

An important (and not immediately obvious) manifestation of the effect of k and its dependency on θ occurs in layered systems of contrasting soil types.[58,59] When a wetting front, moving downward in an unsaturated soil of relatively fine pore sizes, contacts a predominantly large-pore soil, the pore volume capable of holding water at the suction pressure existing at the wetting front is reduced. Before the wetting front can advance, the suction pressure in the upper layer must decrease until it is low enough to allow the pores to fill with water.

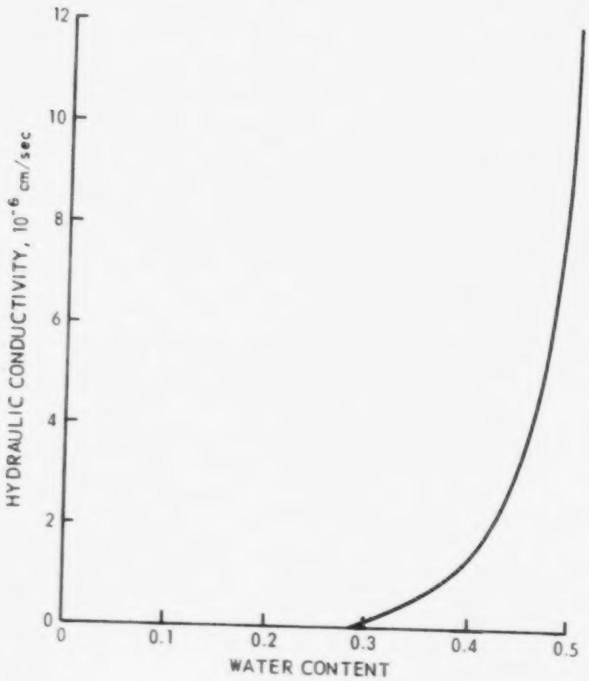


Figure 44. Relationship between hydraulic conductivity and volumetric water content for a clay soil.[57]

This hang-up or delay continues until the upper layer approaches saturation, at which time the water is believed to descend along localized channels[58] rather than as a planar wetting front. Where the coarsely pored soil overlies the finer layer, a similar process reduces the rate of flow to an evaporation surface above.[59]

DETERMINING INFILTRATION

Numerous methods have been proposed for obtaining infiltration and infiltration rate. Theoretically based methods[57] tend to be highly simplified and require special determinations of properties and are not reviewed here. Infiltration is important as direct input into analysis of percolation as explained under WATER BALANCE ANALYSIS OF PERCOLATION FOR DESIGN.

Infiltrometer Measurement

The obvious and often preferred method of determining infiltration rate is by the use of an infiltrometer. In simplest form, the infiltrometer is a metal tube forced into the soil through a test section of the solid waste cover. The tube projects above the surface, and within this space a reservoir of water is maintained. Careful monitoring of the amount of water added to hold a constant reservoir depth is used to develop the infiltration curve.

A preferred infiltrometer also includes an outer concentric ring within which a second reservoir is maintained (Figure 45). This outside reservoir produces a buffer to minimize the lateral spreading of water below the inner tube. Realistically simulating the cover-solid waste interface in a test section of cover may require special care. Where the solid waste is coarse textured and porous, a reasonable degree of similarity may be obtained by using a gravel drainage layer below the test cover. However, see complications discussed under Flow in Unsaturated Soil.

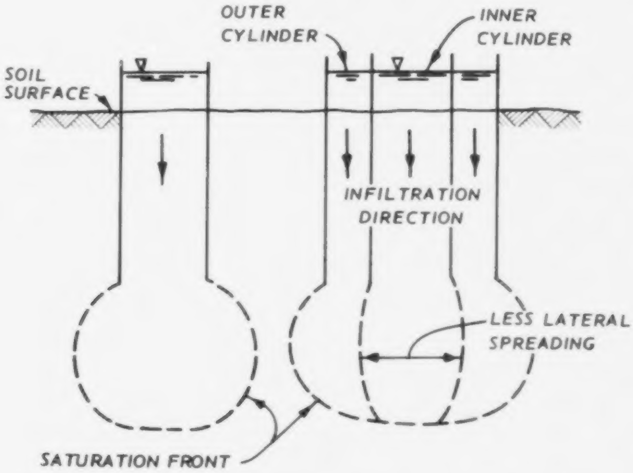


Figure 45. Infiltration as measured by field infiltrometers.

Surface Measurement

Infiltration can also be calculated as a by-product of determination of the runoff coefficient by surface measurements. The runoff coefficient is the percentage of total precipitation that flows off the surface; infiltration accounts for the remainder. Actual runoff measurements may be obtained by carefully fencing a test plot of the landfill or a test section of the proposed cover system. Representative vegetation should be included since vegetation is important in separation of runoff and infiltration. A rain gage should be located nearby to record the precipitation day to day or for even closer increments of time. Important factors in establishing a runoff plot are an adequate system for collecting and storing runoff, a barrier fence that does not intercept rainfall from beyond the immediate plot, and contingencies for high precipitation rates.

Available Runoff Coefficients

Infiltration can be estimated easily where reliable runoff coefficients are available. Considerable work has been done in developing more or less standard runoff coefficients for various agricultural and engineering situations (Table 13).

TABLE 13. EMPIRICAL VALUES FOR OBTAINING RUNOFF COEFFICIENT

Site Description	Value v'
Topography	
Flat land, with average slopes of 1 to 3 ft/mile	0.30
Rolling land, with average slopes of 15 to 20 ft/mile	0.20
Hilly land, with average slopes of 150 to 250 ft/mile	0.10
Soil	
Tight impervious clay	0.10
Medium combinations of clay and loam	0.20
Open sandy loam	0.40
Cover	
Cultivated lands	0.10
Woodland	0.20

* Add values v' for topography, soil, and cover, and subtract from unity to obtain runoff coefficient (adapted from M. M. Bernard (Transactions, American Society of Civil Engineers, 1935)).

Occasionally, it may be appropriate to choose two or more runoff coefficients to be used according to different antecedent water conditions.[55] This conclusion follows from the phenomenon previously described in which the infiltration rate decreases during a rainstorm. A somewhat higher runoff coefficient should be used after a period of heavy rainfall or perhaps to represent the entire wet season.

ASCE Method

Infiltration capacity values for bare soil of three broad classes are provided (Table 14) as the basis of the ASCE empirical method.[60] These values have been developed for semiloose soil wetted 24 hours previously in conditions equivalent to July in the central United States. Soils classified "High" in the table include, besides sand, the open-structured soils of other textures, particularly the most friable silt loams. The higher values of f_1 in the range indicated are ordinarily associated with relatively loose and porous sandy soils. The central values of f_1 for "Intermediate" soils are associated with the loams typical of the better agricultural regions. These loams contain considerable clay and much silt but are friable at ordinary water contents. The "Low" soil class includes not only most clays and clay loams but also other soils that are dense in structure. The higher values of f_1 are ordinarily associated with heavy loams characterized by high clay content, dense structure, and excessive swell/shrink behavior. "Low" soils

TABLE 14. TYPICAL f_1 VALUES FOR BARE SOILS[60]

Soil Class	f_1* (in./hr)
High (sandy soil)	0.50 - 1.00
Intermediate (loam, clay, silt)	0.10 - 0.50
Low (clay, clay loam)	0.01 - 0.10

* f_1 is the infiltration capacity after 1 hr of continuous rainfall.

are commonly deeply cracked, and the initial infiltration rate may be high; however, soon after wetting, the cracks are closed and f_1 decreases rapidly to a more characteristic, low rate.

Table 14 should be supplemented with Table 15, which provides a vegetation factor N for the relationship for the infiltration capacity of vegetated soil,

TABLE 15. VEGETATION COVER FACTOR FOR ESTIMATING INFILTRATION CAPACITY[60]

Vegetation	Cover	Cover Factor, N
Permanent forest and grass	Good	3.0 - 7.5
	Medium	2.0 - 3.0
	Poor	1.2 - 1.4
Close-growing crops	Good	2.5 - 3.0
	Medium	1.2 - 2.0
	Poor	1.1 - 1.3
Row crops	Good	1.3 - 1.5
	Medium	1.1 - 1.3
	Poor	1.0 - 1.1

$$f_{1v} = Nf_1 \tag{7}$$

Grass cover classes are as follows: good--dense vegetal cover of high-quality grass having extensive root systems, properly managed in grass for several years; medium--30-80 percent of "good" vegetal quality and density, well managed in grass for at least 2 years; poor--less than 30 percent of "good" vegetal density, low-quality grass and poor management.

Curve Number Method

The SCS curve number (CN) method[55] is widely used for predicting direct runoff (and in turn infiltration) from rainfall. Total daily rainfall is the usual basis and rainfall intensity is largely ignored. Graphical solutions for the runoff are given in Figure 46. In Table 16 the four hydrologic soil groups distinguished in the method are briefly described and correlated with types of cover for solid waste.

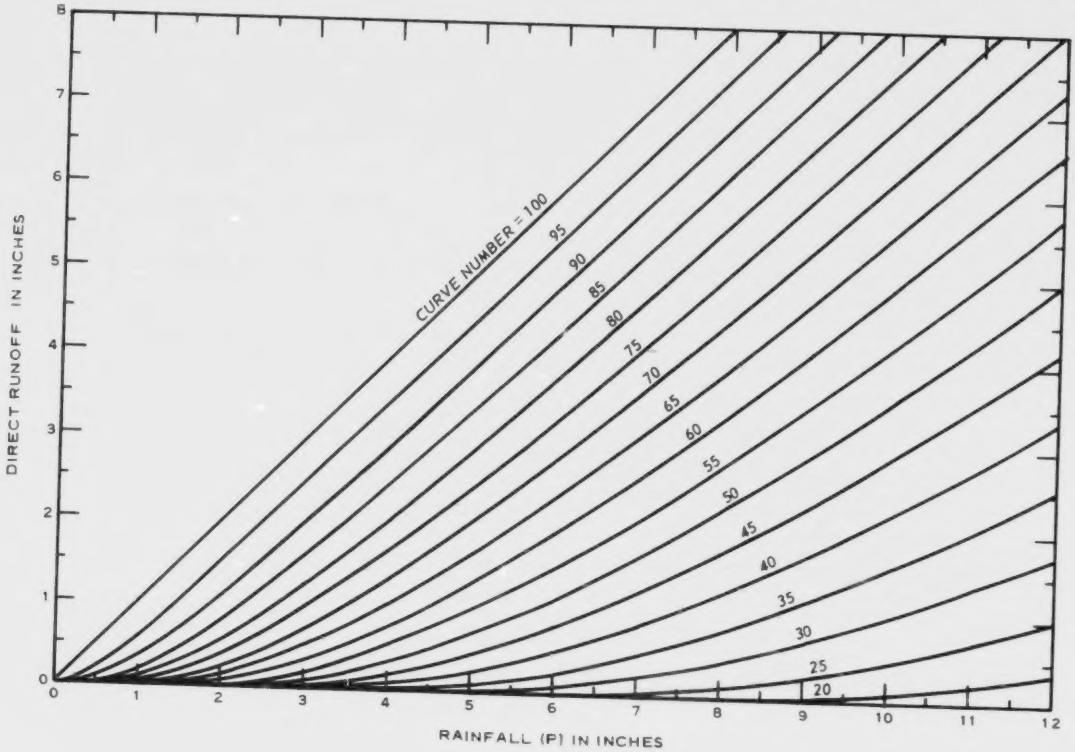


Figure 46. Estimation of direct runoff amounts from storm rainfall (modified from Reference 55).

Vegetation is also important, and curve numbers for several combinations of hydrologic soil group and land use or vegetation are given in Table 17. These curve numbers are for the intermediate antecedent moisture condition (AMC II). Where conditions of greater or lesser antecedent rainfall (Table 18) prevail (AMC I or AMC III), the curve number is adjusted downward or upward, respectively (Table 19).

A major problem for the designer of cover over solid waste arises in anticipating and designating the condition and health of the vegetation. Consider the common case where the designer preliminarily estimates that a vegetated sanitary landfill cover will be similar to a pasture/range or a

TABLE 16. HYDROLOGIC SOIL GROUPS USED BY THE SOIL CONSERVATION SERVICE[61]

Hydrologic Soil Group	Soils Included*	Final Constant Infiltration Rate, f_c in./hr
A	(Low runoff potential) Soils having high infiltration rates even when thoroughly wetted, consisting chiefly of sands or gravel that are deep and well to excessively drained. These soils have a high rate of water transmission.	0.30 - 0.45
B	Soils having moderate infiltration rates when thoroughly wetted, chiefly moderately deep to deep, moderately well to well drained, with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission.	0.15 - 0.30
C	Soils having slow infiltration rates when thoroughly wetted, chiefly with a layer that impedes the downward movement of water or of moderately fine to fine texture and a slow infiltration rate. These soils have a slow rate of water transmission.	0.05 - 0.15
D	(High runoff potential) Soils having very slow infiltration rates when thoroughly wetted, chiefly clay soils with a high swelling potential; soils with a high permanent water table; soils with a clay pan or clay layer at or near the surface; and shallow soils over nearly impervious materials. These soils have a very slow rate of water transmission.	0 to 0.05

* Soils are classed in the next lowest category when a high percentage of stones is present.

meadow. In Table 17, there still remains a large range of choices of curve numbers. In fact, the pasture/range category approaches the full range of the table. In the extreme case of hydrologic soil group A, the curve number ranges from 6 for a contoured pasture or range in good condition to as much as 68 for a pasture or range in poor condition without contouring.

Holtan Equation

In the Holtan equation,[63] infiltration capacity is a function of the volume of available soil water storage and of the permeability of the confining horizon. The computation proceeds according to the empirical relation

TABLE 17. RUNOFF CURVE NUMBERS FOR SOIL-COVER COMPLEXES AT AMC II[55, 62]

Cover			Hydrologic soil group			
Land use	Treatment or practice	Hydrologic condition	A	B	C	D
Fallow	Straight row	----	77	86	91	94
Row crops	"	Poor	72	81	88	91
	"	Good	67	78	85	89
	Contoured	Poor	70	79	84	88
	"	Good	65	75	82	86
	" and terraced	Poor	66	74	80	82
	" " "	Good	62	71	78	81
Small grain	Straight row	Poor	65	76	84	88
	"	Good	63	75	83	87
	Contoured	Poor	63	74	82	85
	"	Good	61	73	81	84
	" and terraced	Poor	61	72	79	82
	" " "	Good	59	70	78	81
Close-seeded legumes* or rotation meadow	Straight row	Poor	66	77	85	89
	" "	Good	58	72	81	85
	Contoured	Poor	64	75	83	85
	"	Good	55	69	78	83
	" and terraced	Poor	63	73	80	83
	" " "	Good	51	67	76	80
Pasture or range		Poor	68	79	86	89
		Fair	49	69	79	84
		Good	39	61	74	80
	Contoured	Poor	47	67	81	88
	"	Fair	25	59	75	83
	"	Good	6	35	70	79
Meadow		Good	30	58	71	78
Woods		Poor	45	66	77	83
		Fair	36	60	73	79
		Good	25	55	70	77
Farmsteads		----	59	74	82	86
Roads (dirt)**		----	72	82	87	89
(hard surface)**		----	74	84	90	92

* Close-drilled or broadcast.

** Including right-of-way.

$$f = GIaS_a^{1.4} + f_c \tag{8}$$

where f = infiltration capacity in inches per hour

GI = growth index of vegetation in percent of maturity

a = infiltration capacity in inches per hour per $(\text{inch})^{1.4}$ of available storage

S_a = available storage in equivalent inches of water

f_c = constant rate of infiltration

TABLE 18. SEASONAL RAINFALL LIMITS FOR ANTECEDENT MOISTURE CONDITIONS[55]

AMC Group	Total 5-day Antecedent Rainfall Dormant Season in.	Total 5-day Antecedent Rainfall Growing Season in.
I	<0.5	<1.4
II	0.5-1.1	1.4-2.1
III	>1.1	>2.1

TABLE 19. CURVE NUMBERS FOR ANTECEDENT MOISTURE CONDITIONS I AND III[55]

CN for Condition II	CN for Conditions I	CN for Conditions III	CN for Condition II	CN for Conditions I	CN for Conditions III
99	97	100	50	31	70
90	78	96	40	22	60
80	63	91	30	15	50
70	51	85	20	9	37
60	40	78	10	4	22
			5	2	13

The vegetative factor a , estimated from Table 20, is an index of surface-connected porosity and a function of plant root density. The growth index GI is calculated from relations between air temperature and the range of temperatures needed for growth of the particular crop.[63] Figure 47 illustrates an example of annual distribution of weekly GI values. For a landfill cover vegetated with grass, the discontinuities for harvesting would be absent, and the overall distribution is similar to potential evapotranspiration as calculated by Holtan.[63] Values of f_c most commonly used in Equation 8 are those listed in Table 16.

Frozen Soil Conditions

Moisture content at the time of freezing is highly important to infiltration, though other factors, such as vegetated versus bare surface, are capable of exerting strong modifying effects. The following summation on soil freezing and effects on infiltration capacity has been offered.[53] The effect is basically a manifestation of the blockage of pores and storage space by ice.

TABLE 20. TENTATIVE ESTIMATES OF VEGETATION PARAMETER "a" FOR INFILTRATION EQUATION*63

Vegetation	Basal Area Rating a Poor Condition	 Good Condition
Fallow	0.10	0.30
Row crops	0.10	0.20
Small grains	0.20	0.30
Hay:		
Legumes	0.20	0.40
Sod	0.40	0.60
Pasture:		
Bunchgrass	0.20	0.40
Temporary (sod)	0.40	0.60
Permanent (sod)	0.80	1.00
Woods and forests	0.80	1.00

* For Equation 8.

a. If soil is frozen (late in the fall) while at a high moisture content or an impervious layer develops at the surface due to refreezing of meltwater at the time of the thaw, intake rate is very low and remains reasonably constant.

b. If soil is at a low moisture content, but its temperature is below freezing, meltwater entering the soil is frozen in the pores and intake rate decreases very rapidly to near zero.

c. Occasionally, soil is frozen at moderately high moisture content (70-80 percent field capacity), yet some of the meltwater is able to penetrate and transfer heat and in turn to melt the ice in pores. As the soil warms and more ice melts, the infiltration rate increases as much as six to eight times its initial rate.

DETERMINING EVAPOTRANSPIRATION

Evapotranspiration is usually the main process by which a cover soil loses water, so it is a major factor in determining percolation (see WATER BALANCE ANALYSIS OF PERCOLATION FOR DESIGN). The methods below are available for estimating potential or actual evapotranspiration. Actual evapotranspiration is a closer estimate of real losses, taking into account on a periodic basis the water actually available for plant use. During a period of subnormal or no precipitation, actual evapotranspiration falls below potential evapotranspiration of the crop.

Lysimeter Measurements

A lysimeter for measuring actual evapotranspiration consists of an

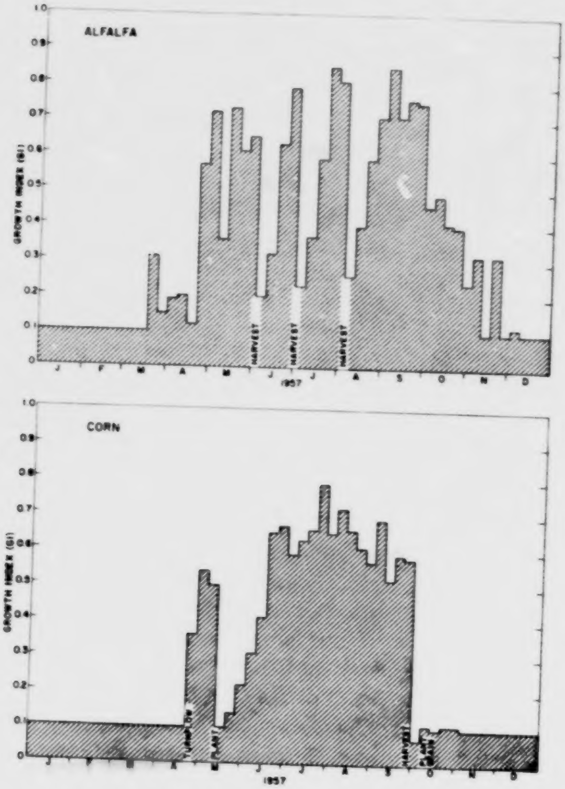


Figure 47. Relative growth (GI) graphs for alfalfa modified by cutting and for corn as modified by tillage.[63]

upright vegetation-soil cell so designed that input water and water percolating out the bottom can be accurately measured; the difference is evapotranspiration. Direct measurements of evapotranspiration will usually only be feasible where the designer has access to the special skills of agricultural engineers. Such talent is found in universities and agricultural agencies.

Pan Evaporation Adjusted

A considerable background has been developed in measuring or estimating evaporation from free water surfaces (Figure 48). Most commonly, an evaporation pan is used so that water loss can be accurately measured. Since evaporation from a typical pan, 4 ft in diameter and 10 in. deep, differs from free water evaporation, a pan coefficient is applied to the pan evaporation value. The range of pan coefficients spans the value 0.7,[64] which is an adequate approximation.

It has been suggested that the rate of transpiration is about the same as the rate of evaporation from a free water surface provided the availability

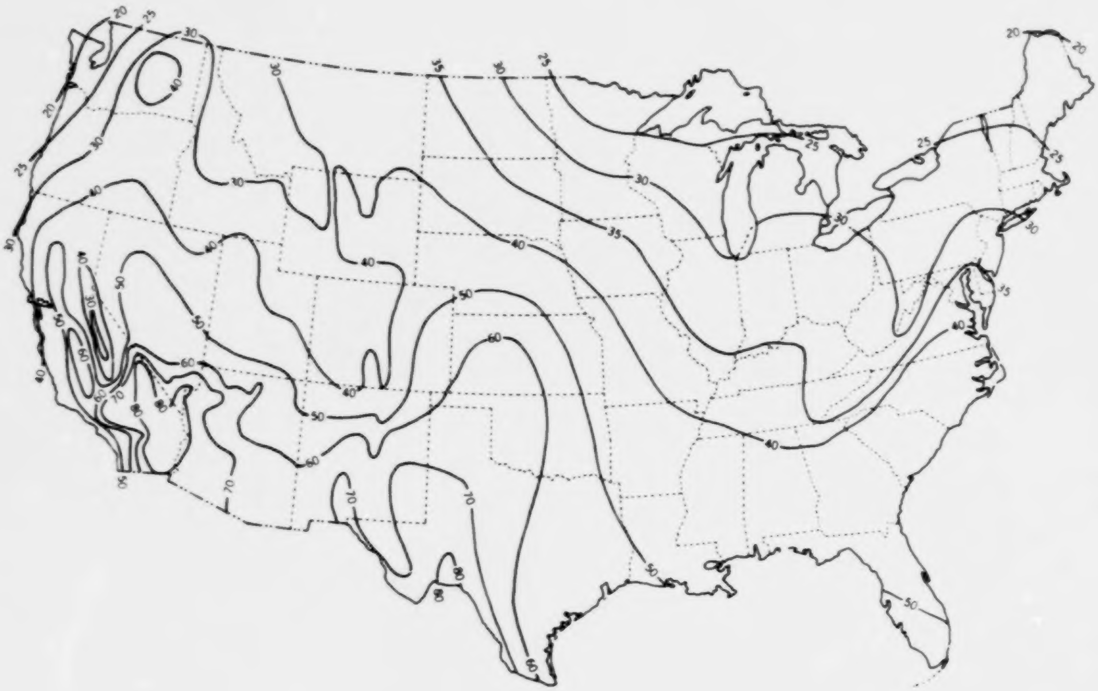


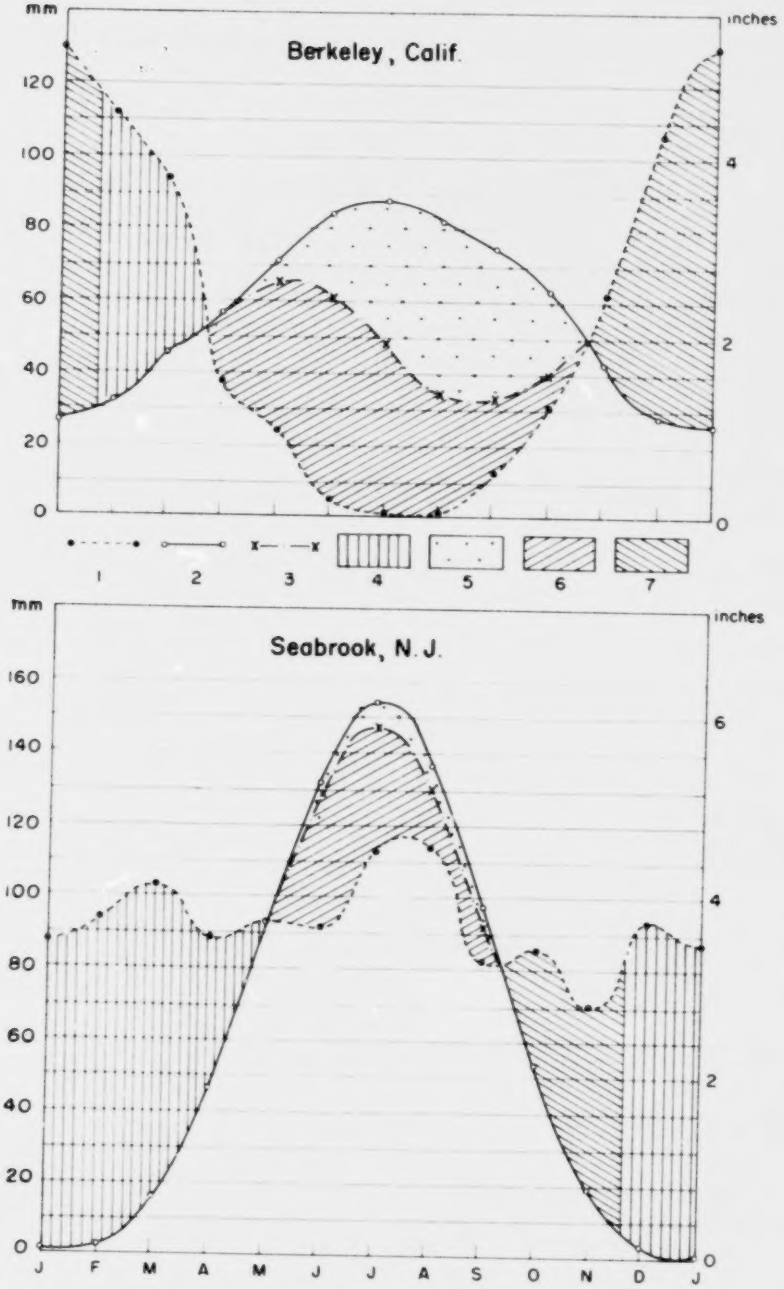
Figure 48. Average annual lake evaporation in inches, according to the National Weather Service.

of water to the plants is not restricted. Therefore, where vegetation remains all year long and prevents essentially all evaporation from soil, the estimated free water evaporation may be assumed to approximate potential evapotranspiration. To obtain the annual distribution of potential evapotranspiration by this method, simply multiply pan evaporation, month by month or at shorter intervals, by an approximate factor, e.g., 0.7. Obviously, estimations of evapotranspiration based on pan evaporation values lack sensitivity to differences from crop to crop.

Thornthwaite Method

An empirical calculation that has remained popular since introduced many years ago is the Thornthwaite method.[65] In order to determine potential evapotranspiration, mean monthly (or closer interval) values of temperature are used; adequate records are available from the National Climatic Center or local sources. Three steps are involved. A heat index is obtained for each of the 12 months and summed for the annual index. Daily potential evapotranspiration is obtained from the heat index by use of tables. Finally, the potential evapotranspiration is adjusted for month and day lengths with correction factors also provided in tables.

Figure 49 presents the potential evapotranspiration curves for Seabrook, New Jersey, and Berkeley, California, calculated on a monthly basis, in relation to precipitation and changes in soil moisture. A minor obstacle to using



NOTE: ANNUAL MARCH OF PRECIPITATION (1), POTENTIAL EVAPOTRANSPIRATION (2), ACTUAL EVAPOTRANSPIRATION (3), PERIODS OF WATER SURPLUS (4), WATER DEFICIT (5), SOIL MOISTURE UTILIZATION (6), AND SOIL WATER RECHARGE (7).

Figure 49. Potential evapotranspiration curves calculated on a monthly basis.[66]

the Thornthwaite method is the necessity of access to the appropriate reference and tables.[65] The library of a university or technical organization or agency may solve this problem.

Consumptive Use

The basic importance of water to crop success has led to an accumulation of information on specific crop requirements. In the western United States, the consumptive use facilitates prediction of the amount of irrigation needed to supplement relatively low natural precipitation. Consumptive use is often lumped on an annual basis for a given crop in a given area, but its distribution over a growing season can be estimated rather well. This estimation may be accomplished on the basis of agricultural experience with the crop or with the aid of another evapotranspiration model. Table 21 provides some example values of consumptive use from the literature.

TABLE 21. EXAMPLES OF CONSUMPTIVE USE IN WESTERN UNITED STATES

Crop	Location	Consumptive Use ft/year
Alfalfa	Los Angeles, CA	3.1, 3.5
Alfalfa	Bonners Ferry, ID	2.8
Alfalfa	Mesa, AZ	4.3
Pasture	Los Angeles, CA	3.5
Wild Hay	Grays Lake, ID	2.6
Grass/Weeds	San Bernardino, CA	1.8
Small Grain	Los Angeles, CA	1.6
Oats	Scottsbluff, NB	1.2
Wheat	Bonners Ferry, ID	1.5
Wheat	San Luis Valley, CO	1.2

DETERMINING WATER STORAGE CAPACITY

Two factors largely determine the water-holding capacity of a soil cover over solid waste, pore characteristics and thickness of the layer. Water storage capacity is basic to percolation analysis as explained under WATER BALANCE ANALYSIS OF PERCOLATION FOR DESIGN.

Soil Characteristics

The water-holding capacity of soil can be described in several ways depending upon the specific interest. Total water capacity has significance in freshly compacted soils (Figure 11). However, with the introduction and development of vegetation, some degree of aggregation develops, and the total soil water content no longer represents a simple component. One may then distinguish gravitational water, available water, and unavailable water (Figure 9) as discussed under AGRICULTURAL INDICES in Section 3.

Water content above field capacity is by definition at best only detained in the soil. When free to do so, it will drain by gravity. That portion of contained water below the wilting point percentage is tightly bound in the soil and not extractable by plants. The most important water to healthy vegetation is that percentage available between the wilting point and field capacity. Figure 9 and Table 22 summarize percentages of the three states of soil water through the range of USDA soil types. Other estimates are available also.[67,68] The designer should establish a basis for selection among these data or for choosing from another source instead after consultation with experts or careful consideration of conditions at the specific site. Remember to consider conditions expected once the vegetation has been established.

TABLE 22. HYDROLOGIC CAPACITIES OF TEXTURE CLASSES[61]

Texture Class	Storage Capacity percent	Large Pores percent	Plant-available Porosity percent
Coarse sand	24.4	17.7	6.7
Coarse sandy loam	24.5	15.8	8.7
Sand	32.3	19.0	13.3
Loamy sand	37.0	26.9	10.1
Loamy fine sand	32.6	27.2	5.4
Sandy loam	30.9	18.6	12.3
Fine sandy loam	36.6	23.5	13.1
Very fine sandy loam	32.7	21.0	11.7
Loam	30.0	14.4	15.6
Silt loam	31.3	11.4	19.9
Sandy clay loam	25.3	13.4	11.9
Clay loam	25.7	13.0	12.7
Silty clay loam	23.3	8.4	14.9
Sandy clay	19.4	11.6	7.8
Silty clay	21.4	9.1	12.3
Clay	18.8	7.3	11.5

Root Layer Depth

The thicker the cover soil, the greater will be the water storage capacity. Actually, the storage capacity of most concern is that of water available to plant use, i.e., in the root zone, since water above field capacity is assumed to drain away quickly vertically or laterally. In agricultural situations, the root zone is on the order of 4 ft thick, but at a solid waste disposal site, it will be limited by the thickness of cover, i.e., the solid waste cell itself is presumed inhospitable to vegetation root systems.

Storage Calculation

The calculation of storage capacity reduces to obtaining the best estimate of available water content, based largely on soil type, and to adjusting the estimate for the thickness of the root zone. For example, consider a 2-ft cover of silty loam over solid waste. Figure 9 for agriculture soils shows that this cover should hold approximately 2 in. of water per foot of soil since the wilting point is approximately 1.4 in. and the field capacity 3.4 in. Accordingly, the storage capacity for the 2-ft root zone, i.e., the full thickness of solid waste cover, is estimated to be 4 in. of water.

WATER BALANCE ANALYSIS OF PERCOLATION FOR DESIGN

The water balance analysis can be conducted on several levels of detail according to the needs of the designer. Gross estimates of percolation may be made in a preliminary manner, or details can be developed using a more elaborate accounting method, such as monthly balancing. Results of analysis using mathematical models and computers are summarized at the end of this subsection.

Disadvantages of water balance analysis are that an empirical runoff coefficient and other parameters requiring experience and engineering judgment for estimation are used and that the various forms of output including percolation are not usually checked by field measurement. Therefore, an overestimation of another output quantity may lead to a serious underestimation of percolation, which is the primary interest. Several terms are abbreviated: percolation (PRC), precipitation (P), runoff (RO), consumptive use (CU), infiltration (I), potential evapotranspiration (PET), actual evapotranspiration (AET), and change in storage (ΔST).

Gross Estimate

The amount of percolation can be grossly predicted on the basis of either of the following annual (Ann.) water balance equations:

$$\text{Ann. PRC} = \text{Ann. P} - \text{Ann. RO} - \text{CU} \tag{9}$$

$$\text{Ann. PRC} = \text{Ann. P} - \text{Ann. RO} - 0.7\ \text{Ann. pan evaporation} \tag{10}$$

For example, assume that the 20-year average annual P (ignoring snow) at Chippewa Falls, Wisconsin, is 24.5 in. Assume that a reasonable runoff coefficient for this site is 0.065[69] and that annual CU for grass is 20 in. of water. For the continuity dictated by Equation 9, the annual PRC is grossly estimated to be 3.0 in.

Monthly Balance

The water balance method using a monthly increment of time has recently been demonstrated to be a useful tool for assessing cover at waste disposal sites.[67] Monthly hydrologic and climatologic data are used to compute monthly infiltration (P - RO); then soil water storage and evapotranspiration estimates are incorporated to obtain average monthly (Mth.) percolation into the waste, i.e.,

$$\text{Mth. PRC} = \text{Mth. P} - \text{Mth. RO} - \text{Mth. AET} - \Delta\text{ST} \qquad (11)$$

A thorough review can be found in Reference 67, but the necessary tables and details of procedure and calculations are only available in Reference 65.

An example of monthly water balance analysis is provided here as a review of the procedure. Consider again the hypothetical site at Chippewa Falls, Wisconsin. This location represents a region where appreciable snow and ice accumulate during the winter; it supplements the three sites considered previously[67] having little snow (Cincinnati, Orlando, and Los Angeles). The selection of Chippewa Falls also allows for direct comparison with an analysis performed on an actual site nearby using a somewhat abbreviated procedure.[69]

A tabulation is arranged in columns of months with a summary column for annual totals (Table 23). On the first line, monthly amounts of P are distinguished as snow or rain according to the season. All precipitation in December, January, and February is considered to be snow that runs off during the spring melt. An average rainfall runoff coefficient was back-calculated for this area[69] by applying the SCS curve number method to actual rainfall events for a 20-year period. Subtracting line RO from line P provides I , the moisture available for infiltration. The PET was obtained[69] by distributing the CU of a grasslike crop over the growing season in a Thornthwaite distribution.

The remainder of the accounting is like that in Reference 67. The quantity (I - PET) pinpoints periods of moisture excess and deficiency in the soil. A negative value indicates the amount by which I fails to supply the potential water need of the cover vegetation. A positive value indicates the excess water that is available for recharge or percolation.

Soil moisture storage (ST) is obtained following the concepts described under DETERMINING WATER STORAGE CAPACITY. The value 1.05 in. at capacity is assigned in humid areas to the last month having a positive value of (I - PET), i.e., end of the wet season, in June at Chippewa Falls (Table 23). To determine the soil moisture retained in subsequent months of water deficiency, consult tables of soil moisture retention in Reference 65.

After finding storage for each month with negative value of (I - PET), add each positive value of (I - PET) representing an addition of moisture to the soil to the previous month's ST value. The value of ST cannot exceed field capacity, and any excess of (I - PET) above this maximum becomes percolation. In the Chippewa Falls example, percolation occurs in the two periods between the summer and winter when (I - PET) is positive and ST is at 1.05 in. On the other hand, as soil moisture is depleted, AET decreases below PET by the difference between (I - PET) and ΔST . Where (I - PET) is positive, the rate of evapotranspiration is not limited by moisture availability and AET equals PET .

TABLE 23. MONTHLY WATER BALANCE ANALYSIS
IN INCHES FOR CHIPPEWA FALLS, WISCONSIN*

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann.
Average Precipitation (P)	0.89†	0.71†	0.77‡ 0.77‡	2.55	3.73	4.19	3.65	3.56	3.37	2.04	0.67‡ 0.67‡	1.00†	4.04 24.53
Runoff (RO)			0.05	0.17	0.24	0.27	0.24	0.23	0.22	0.13	0.04		1.59
Moisture available for infiltration (I)	0.00	0.00	0.72	2.38	3.49	3.92	3.41	3.33	3.15	1.91	0.63	0.00	22.94
Potential evapotranspiration (PET)	0.00	0.00	0.00	1.10	2.50	3.90	4.60	4.00	2.70	1.20	0.00	0.00	20.00
(I - PET)	0.00	0.00	0.72	1.28	0.99	0.02	-1.19	-0.67	0.45	0.71	0.63	0.00	
(Σ neg (I - PET))						(0)	-1.19	-1.86					
Soil moisture storage (ST)	1.05	1.05	1.05§	1.05	1.05	1.05	0.27	0.13	0.58	1.05	1.05	0.05	
(ΔST)	0.00	0.00	0.00	0.00	0.00	0.00	-0.78	-0.14	+0.45	+0.47	0.00	0.00	
Actual evapotranspiration (AET)	0.00	0.00	0.00	1.10	2.50	3.90	4.19	3.47	2.70	1.20	0.00	0.00	19.06
Percolation (PRC)	0.00	0.00	0.72	1.28	0.99	0.02	0.00	0.00	0.00	0.24	0.63	0.00	3.88

* Analysis is modified slightly from that by Dass et al[69] based on a 30-year climate record and a 2-ft silty sand cover with grass.

† Precipitation between November 16 and March 15 is listed as snow but is changed to runoff at spring thaw.

‡ Precipitation in November and March is divided into half rain, half snow.

§ Water-holding capacity is assumed to be at maximum in March when snow melts.

The example water balance analysis was expanded to explore the effects of a much thicker soil cover on percolation (Table 24). A storage capacity of 8 in. was substituted for the soil storage of 1.05 in. from Reference 69, again starting in March. The overall effect on cumulative percolation was small, with a reduction by only about 20 percent. This analysis indicates that increasing cover thickness is not an efficient way of reducing percolation, at least in the northern Midwest.

Woolhiser Plots

A useful group of illustrations has been assembled as a product of a simulation study (Figure 50) of potential percolation from croplands.[62] Woolhiser was able to calculate average annual PRC for a given crop at 52 sites east of the Rocky Mountains using the SCS curve number procedure for RO and subroutines for calculating AET and PRC . The model incorporates sophistication for changing root depth during the growing season. The resulting large collection of data was sufficient for contouring, and maps were prepared that are directly useful for roughly estimating percolation in four soil types (Figures 51 through 54).

Dr. D. A. Woolhiser, USDA Science and Education Administration and Mr. R. J. Montgomery at Colorado State University modified the SCSRO model and computer program for the present study and analyzed the four hydrologic soil groups in a simple, waste cover configuration. Data were generated on average annual percolation through 2 ft of soil with meadow vegetation. When their data are plotted and contoured, it is found that the predictions of annual percolation through 4 ft of type A soil supporting straight-row corn (Figure 51) are about the same as predictions for 2 ft of comparable soil with meadow vegetation. The predictions for B and C soils are less conformable; and, in the extreme, the predictions of annual percolation through 2 ft of type D cover soil in the humid Southeast appear to be as much as 50 percent greater than shown for 4 ft of cropland soil in Figure 54.

USDAHL Program

An empirical mathematical model of hydrologic systems has evolved from work at the USDA Hydrograph Laboratory (HL). Portions of the research have been published previously, but a summary is available[63] along with a listing of the computer program. The model (Figure 55) incorporates in the water balance continuity equation the Holtan equation (Equation 8) for infiltration capacity and an evapotranspiration model based on pan evaporation and an adjustment for growth index (Figure 47).

The USDAHL program, like most other hydrologic models, was primarily designed for predicting surface runoff. Volumes running off the surface exceed those percolating to depth usually, so that the sensitivity of this model for predicting percolation should be considered critically. In fact, an estimation of groundwater recharge (deep percolation) is required as model input.

CRITERIA FOR ALLOWABLE PERCOLATION

Perhaps the greatest challenge in designing a cover for a humid area is

TABLE 24. MONTHLY WATER BALANCE ANALYSIS IN INCHES WITH THICK COVER*

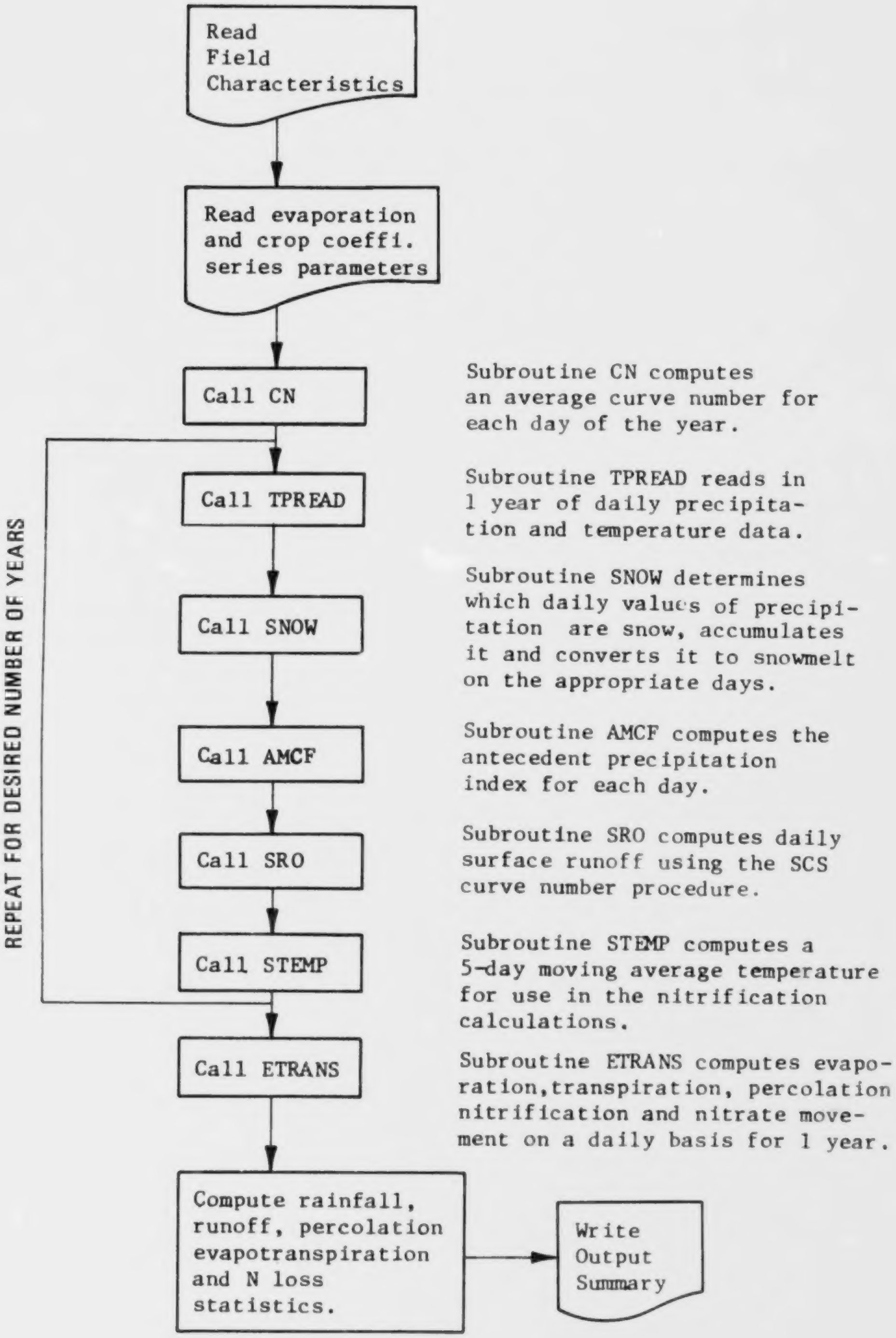
Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann.
Average Precipitation (P)	0.89†	0.71†	0.77‡ 0.77‡	2.55	3.73	4.19	3.65	3.56	3.37	2.04	0.67‡ 0.67‡	1.00†	4.04 24.53
Runoff (RO)			0.05	0.17	0.24	0.27	0.24	0.23	0.22	0.13	0.04		1.59
Moisture available for infiltration (I)	0.00	0.00	0.72	2.38	3.49	3.92	3.41	3.33	3.15	1.91	0.63	0.00	22.94
Potential evapotranspiration (PET)	0.00	0.00	0.00	1.10	2.50	3.90	4.60	4.00	2.70	1.20	0.00	0.00	20.00
(I - PET)	0.00	0.00	0.72	1.28	0.99	0.02	-1.19	-0.67	0.45	0.71	0.63	0.00	
(Σ neg (I - PET))						(0)	-1.19	-1.86					
Soil moisture storage (ST)	8.00	8.00	8.00§	8.00	8.00	8.00	6.89	6.33	6.78	7.49	8.00	8.00	
(ΔST)	0.00	0.00	0.00	0.00	0.00	0.00	-1.11	-0.56	+0.45	+0.71	+0.51	0.00	
Actual evapotranspiration (AET)	0.00	0.00	0.00	1.10	2.50	3.90	4.52	3.89	2.70	1.20	0.00	0.00	19.81
Percolation (PRC)	0.00	0.00	0.72	1.28	0.99	0.02	0.00	0.00	0.00	0.00	0.12	0.00	3.13

* Compare with Table 23.

† Precipitation between November 16 and March 15 is listed as snow but is changed to runoff at spring thaw.

‡ Precipitation in November and March is divided into half rain, half snow.

§ Water-holding capacity is assumed to be at maximum in March when snow melts.


Read
Field
Characteristics
Read evaporation
and crop coeffi.
series parameters
Call CN
Call TPREAD
Call SNOW
Call AMCF
Call SRO
Call STEMP
Call ETRANS
REPEAT FOR DESIRED NUMBER OF YEARS
Compute rainfall, runoff, percolation evapotranspiration and N loss statistics.
Write
Output
Summary

Subroutine CN computes an average curve number for each day of the year.

Subroutine TPREAD reads in 1 year of daily precipitation and temperature data.

Subroutine SNOW determines which daily values of precipitation are snow, accumulates it and converts it to snowmelt on the appropriate days.

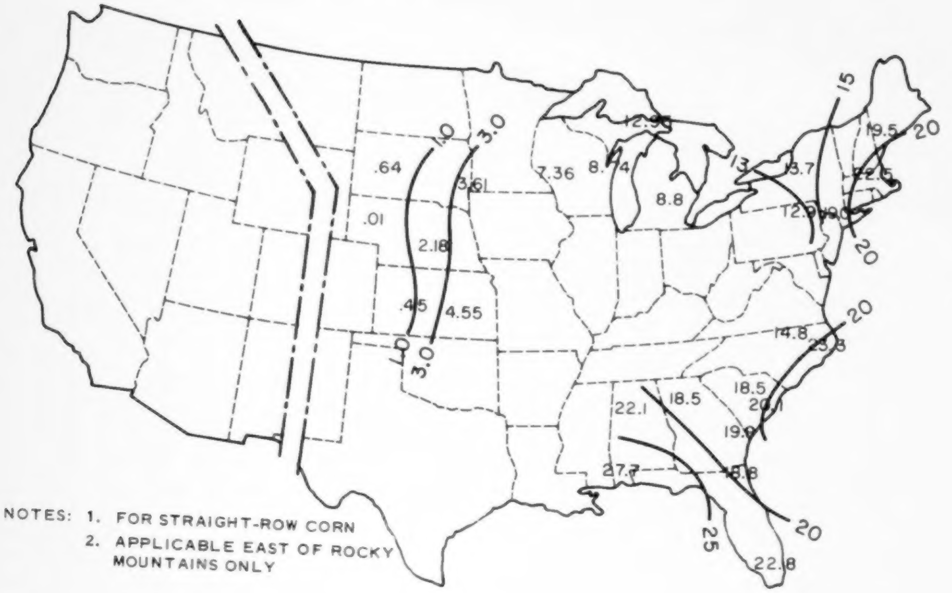
Subroutine AMCF computes the antecedent precipitation index for each day.

Subroutine SRO computes daily surface runoff using the SCS curve number procedure.

Subroutine STEMP computes a 5-day moving average temperature for use in the nitrification calculations.

Subroutine ETRANS computes evaporation, transpiration, percolation nitrification and nitrate movement on a daily basis for 1 year.

Figure 50. Generalized flow chart for Program SCSRO with percolation option.[62]


1.0
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.64
3.61
.01
2.18
.45
4.55
1.0
3.0
7.36
8.74
8.8
13
13.7
15
19.5
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20
14.8
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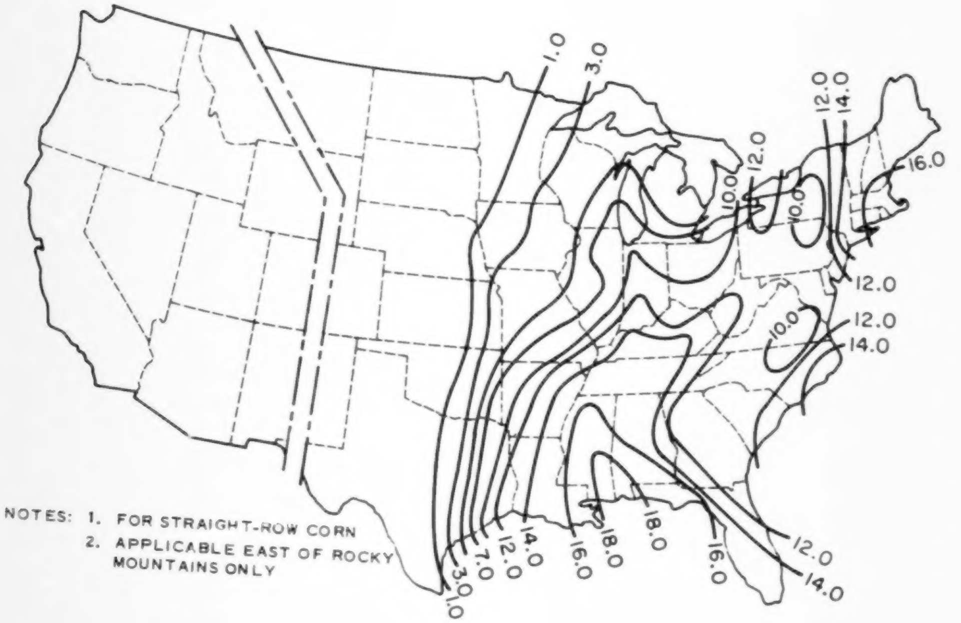
20
18.5
18.5
20.1
22.1
19.9
27.7
15.8
20
25
22.8
NOTES: 1. FOR STRAIGHT-ROW CORN
2. APPLICABLE EAST OF ROCKY MOUNTAINS ONLY

Figure 51. Mean annual percolation in inches below a 4-ft root zone (Hydrologic Soil Group A). Four inches available water-holding capacity.62


1.0
3.0
12.0
14.0
12.0
16.0
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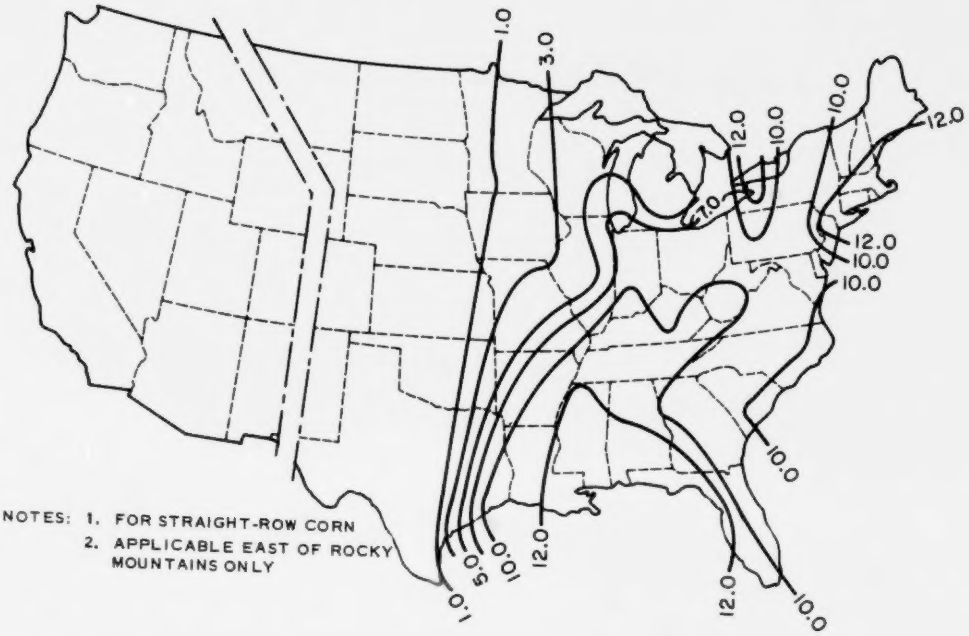
10.0
12.0
10.0
12.0
14.0
1.0
3.0
7.0
12.0
14.0
16.0
18.0
18.0
16.0
12.0
14.0
NOTES: 1. FOR STRAIGHT-ROW CORN
2. APPLICABLE EAST OF ROCKY MOUNTAINS ONLY

Figure 52. Mean annual percolation in inches below a 4-ft root zone (Hydrologic Soil Group B). Eight inches available water-holding capacity.62


1.0
3.0
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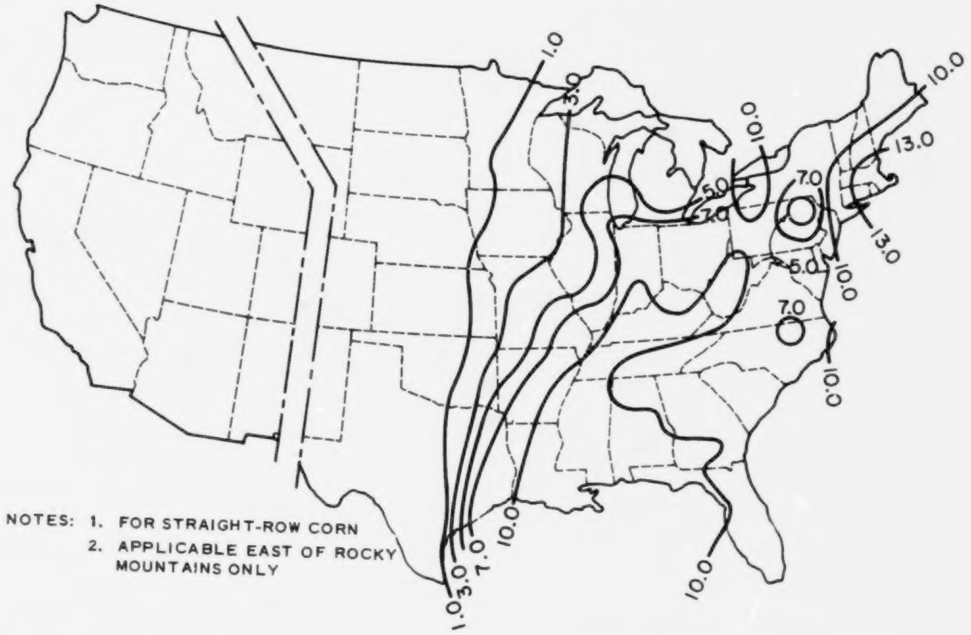
12.0
7.0
12.0
10.0
10.0
10.0
1.0
5.0
10.0
12.0
12.0
10.0

NOTES: 1. FOR STRAIGHT-ROW CORN
2. APPLICABLE EAST OF ROCKY MOUNTAINS ONLY

Figure 53. Mean annual percolation in inches below a 4-ft root zone (Hydrologic Soil Group C). Eight inches available water-holding capacity.[62]


1.0
3.0
10.0
10.0
13.0
5.0
7.0
7.0
13.0
5.0
10.0
7.0
10.0
1.0
3.0
7.0
10.0
10.0

NOTES: 1. FOR STRAIGHT-ROW CORN
2. APPLICABLE EAST OF ROCKY MOUNTAINS ONLY

Figure 54. Mean annual percolation in inches below a 4-ft root zone (Hydrologic Soil Group D) Six inches available water-holding capacity.[62]

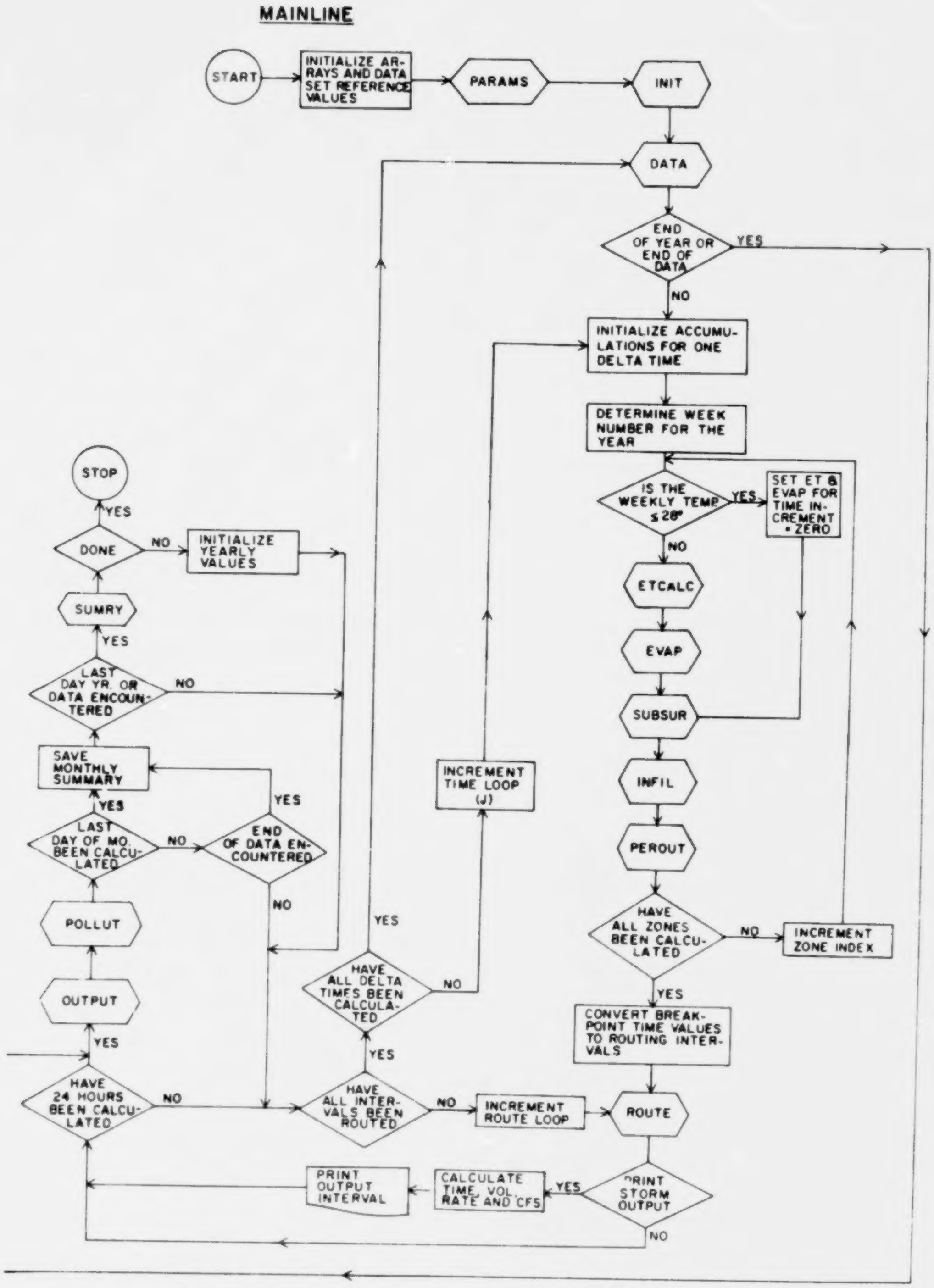

MAINLINE
START
INITIALIZE ARRAYS AND DATA SET REFERENCE VALUES
PARAMS
INIT
DATA
END OF YEAR OR END OF DATA
YES
NO
INITIALIZE ACCUMULATIONS FOR ONE DELTA TIME
DETERMINE WEEK NUMBER FOR THE YEAR
IS THE WEEKLY TEMP ≤ 28°
YES
SET ET & EVAP FOR TIME INCREMENT = ZERO
NO
ETCALC
EVAP
SUBSUR
INFIL
PEROUT
HAVE ALL ZONES BEEN CALCULATED
NO
INCREMENT ZONE INDEX
YES
CONVERT BREAKPOINT TIME VALUES TO ROUTING INTERVALS
ROUTE
PRINT STORM OUTPUT
YES
CALCULATE TIME, VOL, RATE AND CFS
PRINT OUTPUT INTERVAL
NO
INCREMENT ROUTE LOOP
NO
HAVE ALL INTERVALS BEEN ROUTED
YES
HAVE ALL DELTA TIMES BEEN CALCULATED
NO
INCREMENT TIME LOOP (J)
YES
HAVE 24 HOURS BEEN CALCULATED
NO
YES
OUTPUT
POLLUT
LAST DAY OF MO. BEEN CALCULATED
NO
END OF DATA ENCOUNTERED
NO
YES
YES
SAVE MONTHLY SUMMARY
LAST DAY YR. OR DATA ENCOUNTERED
NO
YES
SUMRY
DONE
NO
INITIALIZE YEARLY VALUES
YES
STOP

Figure 55. Flow chart of USDAHL--74 mainline (see Reference 63 for explanation of subroutines).

in establishing what are tolerable limits of percolation. Attempts at solving this problem have been made previously.[67,69] Annual percolation is estimated and used along with an assumed field capacity[67,70,71] (1-4 in./ft) of the waste to estimate the time to field capacity of the waste cell. Upon reaching field capacity, the leachate will be generated at the annual percolation rate. This criterion is valuable in that it offers a starting point, albeit an oversimplified one. Experience shows that a leaking solid waste disposal site becomes a problem before field capacity. Water percolating through the cover usually becomes channelized, especially in heterogeneous solid waste such as from municipal sources.

A more realistic criterion for allowable percolation may be on the basis of what is the tolerable leachate rate. If a system is designed capable of collecting and retaining X in. of leachate (distributed over the landfill area), then that X value will dictate the allowable percolation rate through the cover. Accordingly, the designer may be advised to analyze, besides the average condition, a daily or hourly water balance for the 20-year storm, etc. In this way, extreme throughflows will be incorporated in the design and will not surprise and overwhelm a system designed only for average percolation.

DESIGNING FOR INFILTRATION/PERCOLATION CONTROL

Several of the parameters influencing infiltration and percolation can be manipulated during design and construction. The principal techniques are soil selection or blending, compaction, and layering. Presently, the usual intention is to impede the percolation of water, and the following guidance is oriented in that direction. For cases where the cover is intended to pass water freely, the appropriate procedure should also be apparent in contrast.

Selection of Soil

It was emphasized under Flow in Unsaturated Soils that permeability is a direct indicator of a soil's tendency to allow percolation of water. Accordingly, one of the most useful means of designing a cover to impede the passage of water into solid waste cells is by use of fine-grained soil with inherently low k. Conversely, where relatively free passage of water is needed, the choice of cover soil should be among those with predominantly coarse grain sizes (and high k). Well-graded granular soils have lower k values than poorly graded granular soils (Table 6) provided the median grain size is the same. Table 5 should be useful as a guide in determining the relative effectiveness of various soils in impeding or passing water, but other factors, such as shrinking and cracking characteristics, and root-system development may complicate the choice.

Blending

If well-graded fine soil is not available nearby but coarse- and fine-grained soils are, blending should be considered. As explained in Section 5 soil blending is effective for increasing impedance to water movement, since the grain-size distribution is broadened as compared with distributions of the component soils. Blending is usually an expensive operation, and a thorough review of other options should be made before proceeding on a large scale.

Compaction

As a general rule, the cover should be compacted at all solid waste disposal areas. Compaction is effective in reducing infiltration and percolation; the porosity is decreased and k values sharply reduced. At municipal waste landfills, an effort of more than two passes of the spreading or compacting equipment may be impractical to monitor and regulate. Higher compactive efforts seem appropriate for intermediate and final covers, except as it will interfere with seeding grass. Care should be taken to assure that the water content during compaction does not greatly exceed the optimum percentage.

Layering

Layering achieves effects not obtainable with a single material. A two-layer system should be sufficient for most covers and, in order to impede percolation, might consist of a layer of compacted clay of very low k value beneath a layer of silty sand to support vegetation, to provide erosion protection, and to help retain capillary water in the clay layer. Layering offers promise for significant improvements in cover design, but the geometry and layer composition should be incorporated in the design on a site-specific basis after other options have been considered.

Membranes and Barriers

Numerous impermeable membranes and barriers are available to stop percolation where such a need has been established. The costs are high, and cover systems incorporating such features are ordinarily only specified over hazardous wastes. Section 6 provides a review of such commercial cover materials. Locally, infiltration barriers will serve beneficially as gas barriers also, but elsewhere the two functions are in conflict (see Gas Barriers in Section 9).

Increased Thickness

The principal effects of increasing cover thickness are to increase the water storage capacity, to extend percolation time, and to reduce effects of cracks and settlements. Contrasting effects can develop; the increased storage capacity and root zone may result in more efficient evapotranspiration, but then more water can be stored in the cover for subsequent slow drainage and percolation. Departures from the more or less standard 2-ft thickness should be backed up by an appropriate water balance analysis. Note that increasing thickness and storage is apparently not an efficient design tool (Tables 23 and 24) for reducing percolation (see Discontinuities).

Discontinuities

An otherwise well-designed cover system may be compromised in time if deep cracks or offsets develop. Such discontinuities commonly form in association with differential settlement and, therefore, are aggravated by formation of depressions detaining some runoff. The first step to avoiding discontinuities comes in placement and compaction of the solid waste that forms the base. Heterogeneity should be reduced as much as possible; bulky objects, such as hard frames or elastic tires, should be kept from the upper part of the waste cell. A second beneficial procedure is to increase cover thickness sufficiently so that anticipated differential settlement will not expose the waste cell to direct percolation. Ponding in associated depressions can be avoided by providing sufficient slope.

Surface Slope

Rainfall runoff increases with an increasing slope of the surface; hence infiltration decreases. Since erosion also increases with an increasing slope (see Section 10), the design of the slope should balance opposing considerations (where percolation is undesirable). On slopes of less than 3 percent, the irregularities of the surface and vegetation commonly act as traps for detention of runoff. The value 5 percent has been suggested and used in grounds maintenance[72] as a first approximation of a slope sufficient to promote runoff without risking excessive erosion.

Figure 56 illustrates one detail of slope design peculiar to cover surfaces over spongy solid waste (municipal waste). Allowance should be made for anticipated compaction after placement of solid waste, remembering that settlement will be proportional to waste thickness. Otherwise, pockets of solid waste of anomalously great thicknesses may settle sufficiently in time to compromise the design of surface slopes and drains. Designing slopes much greater than 5 percent may be necessary where such anomalous waste thicknesses are present.

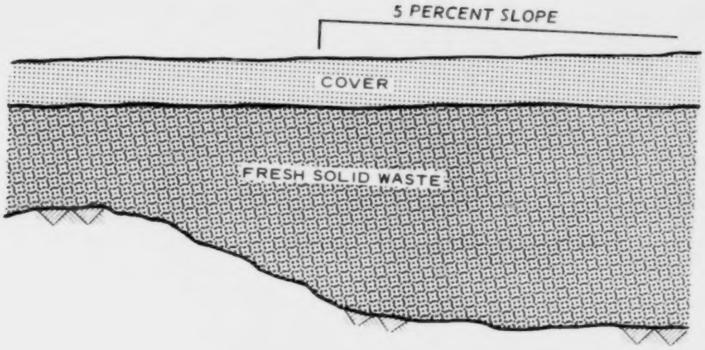
The common circumstance of deposition of solid waste on hillsides will lead to the opposite effect. Settlement of the greater thickness at the outside edge (Figure 56) will cause surface slope to increase in time. Forethought in designing may be necessary here also to avoid increased erosion with increasing slope.

Winter Grass

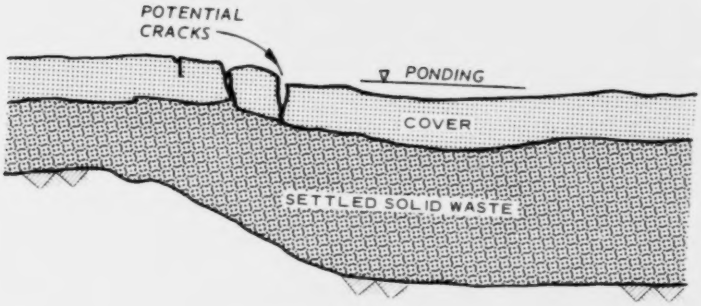
In mild climates, as in the southeastern United States, consideration should be given to growing both summer and winter grass to protect the cover from erosion and to extend the range of evapotranspiration to a year-round basis.

Ditching and Drainage

The first rule of surface drainage design for solid waste sites is to intercept and direct all water from outside the immediate area. Interception is accomplished by constructing a ditch or system of ditches on the uphill sides. The ditch is designed to accommodate anticipated discharge, e.g., a 10-year storm, according to an appropriate hydraulic formula such as the following one intended for flatlands.[36]



a. BEFORE SETTLEMENT



b. AFTER SETTLEMENT

Figure 56. Disruption of surface slope by excessive settlement.

$$Q = CA^{5/6} \qquad (12)$$

where Q = required discharge in cubic feet per second
C = watershed/storm coefficient
A = drainage area in square miles

See various references on hydraulics and drainage to establish a preferred relationship for design.

On the cover itself discharge volumes are small, and the main concern is removing water quickly with minimal damage by erosion. A ditch slope of 2 percent is recommended.[72] Ditches should be grassed, and for proper mowing maintenance, side slopes should not exceed 1 vertical (V) on 3 horizontal (H) or in cases of V-shaped channels, 1V on 6H. Actually, flat-bottomed channels are much preferred to V-shaped channels[72] from the point of view of erosion. See DESIGN FOR WATER EROSION CONTROL for mention of linings and special drop inlets to convey runoff down the steep sides of solid waste sites.

Subsurface Drainage

Removal of cover soil water through buried drains offers promise for effective reduction of percolation into waste cells, since such drains have been proven viable in engineering and agriculture. Buried pipe drains are conduits of fired clay, concrete, metal, etc., with open joints or perforations that collect and convey drainage water.[36] Fired clay has better resistance than metal to corrosive conditions that may arise at solid waste disposal sites. Drains require little maintenance and leave the surface in a natural and aesthetically pleasing condition. A herringbone pattern of drains can be adapted easily to minor topographic irregularities as they are developed in landfilling. Each main drain ordinarily follows a topographic low, and the lateral drains intersect at appropriate intervals. Combinations of buried pipe drains with gravel or sand drains (Figure 57) are even more efficient.

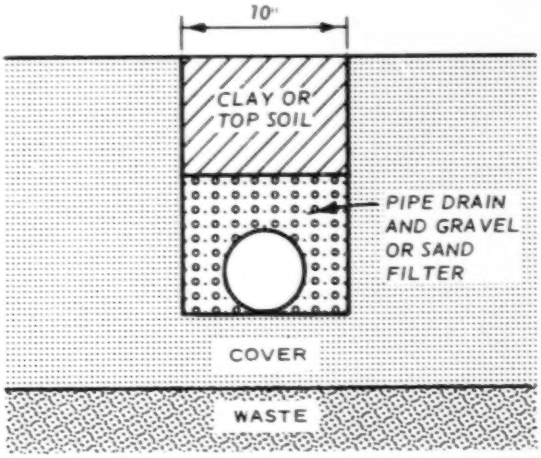


Figure 57. Combined buried pipe drain and gravel or sand drain with cover.

Table 25 should be helpful in estimating adequate spacing of pipe drains.

Maintenance

The overall plan for development and eventual closure of a solid waste disposal site should be supplemented by contingency plans for long-range maintenance and repair to counteract unexpected changes in soil structure, vegetation, slope, and drainage that will in turn affect percolation.

TABLE 25. THE RELATION OF TILE SPACING TO THE HYDRAULIC CONDUCTIVITY OF SOILS

Hydraulic Conductivity in./hr	Tile Spacing, in feet, for Tile Placed at Depth of		
	3 ft	4 ft	5 ft
0.0 - 0.05	0 to 15	0 to 20	0 to 25
0.05- 0.20	15 to 30	20 to 40	25 to 50
0.20- 0.80	30 to 60	40 to 80	50 to 100
0.80- 2.50	60 to 110	80 to 145	100 to 180
2.50- 5.0	110 to 155	145 to 205	180 to 255
5.0 -10.0	155 to 220	205 to 290	255 to 360

SECTION 9

CONTROL OF GAS

Cover commonly serves the function of limiting gas flow paths from solid waste. Elsewhere, control may be passive, e.g., in the case of granular soil cover that allows escape of gas over the large landfill surface area. Since municipal wastes generally produce large quantities of gases, emphasis will be placed on covering municipal wastes in the following discussions.

GAS PRODUCTION IN SOLID WASTE

Organic materials in municipal waste undergo decomposition that gradually changes from aerobic to anaerobic after covering. Carbohydrates, fats, and proteins in the waste are broken down by microbial fermentation and converted to gases and organic residues. The chemical reaction can be represented as follows:[73]

$$C_aO_bH_cN_dS_e \xrightarrow[\text{Bacteria}]{\text{Anaerobic Decomposition}} wCO_2 + xCH_4 + yNH_3 + zH_2S + \text{humus}$$

Carbon dioxide (CO_2) and methane (CH_4) comprise as much as 90 percent of the gases produced. It has been suggested[74] that CO_2 concentrations are highest shortly after waste placement and covering. As the fill ages and decomposition progresses, CO_2 concentrations decrease and level off, whereas CH_4 concentrations tend to increase and level off. Water added to the waste by percolation through the cover accumulates in the waste and at least initially increases the rates of decomposition and gas production.

Alone, CH_4 is not explosive, but when it accumulates at concentrations of 5 to 15 percent in air, it is highly explosive.[75] Since oxygen is virtually void in a densely compacted and sealed landfill when CH_4 is produced, there is no danger of the fill exploding. However, if CH_4 moves through the soil and accumulates in structures, it may cause explosive conditions.

Methane migrating through the sides or top of landfills may adversely affect plant life. Where disposal sites are located next to planted areas, or where parks and recreational areas are planned after disposal operations cease, the effect of CH_4 on plant health is of particular concern.

GAS FLOW THROUGH COVER SOIL

Gases produced in waste cells move in all directions through cover layers and surrounding soil to the atmosphere or adjacent substrata. Flowage takes place either by diffusion or in response to a gradient of total pressure.[76] The total pressure gradient mechanism is usually subordinate in solid waste except in those cases where it is feasible to pump gases into or from waste cells. Flow of gases is dependent on several physical parameters, particularly porosity, degree of saturation, and free space gas diffusivity.

The rate of diffusion through a porous medium, such as soil, is less than through air. The relationship[68,74] for a dry material is

$$D_p = 0.66nD_o \tag{13}$$

where D_p = diffusivity (units of length^2/time) of the porous medium
n = porosity
D_o = free space diffusivity at 20°C

Equation 13 assumes no water present in the pores. In soils, the degree of saturation S, or fraction of void space occupied by water, enters and the relationship becomes

$$D_p = 0.66n(1 - S)D_o \tag{14}$$

In Equation 14, the constant D_o has values of 15 and 21 ft^2/day for CO_2 and CH_4, respectively. As explained in Section 5, n is dependent on the state of compaction of the soil. Table 26 compares n values of several soils in loose and dense conditions, but overall, n varies only within the range of about 30 to 50 percent. Thus, the effect of n on D_p seldom varies by more than a factor of 2. The effect on D_p of variations in S from saturation (100 percent) down to realistic dry conditions of perhaps as little as 2 percent ranges to as much as a factor of 50. This prominent influence of S on the diffusivity of gas through waste covering soil has been demonstrated in a study of vaporization and flux of hazardous chemical waste.[77]

TABLE 26. APPROXIMATE AVERAGE POROSITY OF LOOSE AND COMPACTED SOILS

Soil Type	Average Porosity, % Loose	Average Porosity, % Dense
Gravel	37	28
Uniform sand	46	34
Silty sand	44	37
Clayey sand	44	34
Silt	44	37
Clay	45	

Gas diffusion through a soil cover has been calculated[74] according to the relationship

$$q = D_p\left(\frac{C_o}{L}\right) \qquad (15)$$

where q = discharge velocity (units length/time)
C_o = gas concentration fraction by volume on the confined side of the cover*
L = cover thickness

Gas transfer and effects of changing design features, such as cover thickness and soil type, can be examined using the concepts incorporated in the equation.

Consider for example the following conditions offered as reasonably representing a municipal sanitary landfill[75] covered largely with clay:

Temperature = 68°F
$D_o(CO_2)$ = 15 ft^2/day
$D_o(CH_4)$ = 20.7 ft^2/day
n = 60 percent**
S = 50 percent
L = 3 ft
$C_o(CO_2)$ = 30 percent
$C_o(CH_4)$ = 35 percent

From Equation 14

$$\frac{D_p}{D_o} = 0.66(0.60)(1 - 0.50) = 0.198$$

Equation 15 predicts the following discharge velocities for CH_4 and CO_2, again according to Reference 75:

$$q_{CO_2} = \frac{(0.30)(15\ ft^2/day)(0.198)}{3\ ft} = 0.297\ ft/day$$

$$q_{CH_4} = \frac{(0.35)(20.7\ ft^2/day)(0.198)}{3\ ft} = 0.478\ ft/day$$

For 1 acre, the discharges are:

---

* C_o is actually the difference in concentration on opposite sides of the cover.

** The porosity n = 60 percent is probably estimated too high in this example (see Table 26).

$$Q_{CO_2} = \frac{(0.297\ \text{ft/day})(43{,}560\ \text{ft}^2\text{/acre})(1\ \text{acre})}{(1\ \text{day/24 hr})(1\ \text{hr/60 min})} = 8.98\ \text{ft}^3\text{/min}$$

$$Q_{CH_4} = \frac{(0.478\ \text{ft/day})(43{,}560\ \text{ft}^2\text{/acre})(1\ \text{acre})}{(1\ \text{day/24 hr})(1\ \text{hr/60 min})} = 14.46\ \text{ft}^3\text{/min}$$

DESIGNING FOR CONTROL OF GAS FLOW

The discussions above have summarized the parameters influencing gas flow through cover. The following procedures instituted during the design/construction phase make use of the various factors to help control the flow.

Soil Selection

A cover soil that will maintain a high degree of saturation is most effective in reducing gas flow. A fine-grained soil, such as clay, has more tenacity for capillary water than a coarse granular soil; in other words, the capillary head H_c is greater. Table 5 presents some typical values of H_c for various soils. Figure 9 provides another view of the same concept; over half the water in clay is bound tightly, in contrast to sand with less than 5 percent. In selecting a cover soil to minimize gas movement, the finest grained soil available in adequate quantity will ordinarily be best. Obviously, a sand or gravel is the preferred soil for facilitating gas flow, as in venting systems.

Special Compaction

Decreasing porosity of the soil by specifying appropriate compactive effort is desirable and recommended for intermediate and final cover in order to reduce gas migration. A scheme of quality control should usually be specified to confirm the effectiveness of the compaction.

Increased Cover Thickness

Thickening the cover is a direct and effective procedure for reducing q as indicated by Equation 15. The technique is especially useful for intermediate and final soil covers and in subsequent maintenance work after the disposal operation has ceased.

Gas Barriers

Barriers to gas may be considered where adverse consequences of excessive gas leakage justify their extra cost. Also, they may constitute an important part of systems designed to recover CH_4 as a source of energy. A suitable barrier may be incorporated in a layered cover system, e.g., as a highly compacted layer of damp clay a few inches thick. Impermeable membranes are other possibilities, but overlaps or seams between strips or sheets may be vulnerable to leakage. In all cases, the consequences of effectively restricting the flow of gas should be evaluated. It has been suggested that membranes may even balloon and rupture.[44] It may be necessary to install numerous vents to prevent the forcing of lateral movement to dangerous concentrations in basements and other adjacent spaces.

Layered Cover

Layered soil cover can be effective in blocking and channeling gas movement while providing for support of vegetation and for other cover functions. Figure 32 shows three basic components in one recommended system. The clay layer is the barrier, serving mainly to restrict infiltration of rainwater. The gravel layer below is intended to convey (to vents) the rising gases blocked by the barrier; a secondary value is the level base on which the barrier is founded. The topsoil supports vegetation and helps retain moisture in the clay as explained in Section 5 under LAYERING.

Gas Vents and Channels

Gas channels and vents are used in conjunction with barriers to convey freely the gases along special paths and through the cover to the atmosphere. Figure 58 shows a simple design for venting gases. The access channels may consist of parallel strips of gravel spaced at regular intervals and incorporated at the base of final covering. The strips should be thick enough and wide enough to avoid disruption of their continuity by careless construction or subsequent settlement. Where coarse granular material is plentiful, a continuous blanket is preferred. Pipe drains in the gravel increase effectiveness but do add to expense.

Vertical, gravel-filled trenches about 3 ft wide and 10 ft deep have been used as a remedial feature providing venting through cover on landfills with gas problems.[78] These filled slot vents are effective as long as the backfill

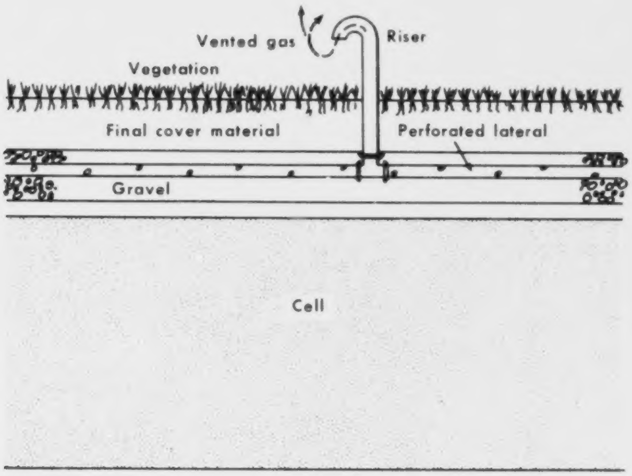


Figure 58. Gas collecting and venting system of laterals in gravel trenches above waste cell.[3]

remains open; clogging along the waste/backfill interface can occur from activity of microorganisms. One disadvantage of granular slots is that rainwater is imbibed directly. Therefore, the slots should be designed to occupy topographic highs to avoid even greater water infiltration from concentration of runoff.

Forced Draft Venting

Forced draft vents offer promise for alleviating difficult gas migration problems. Although powered pumps may be feasible in the future, "attic" turbines are adequate to provide small total pressure differences that can draw gas through wells and vents. Cost is minimal and maintenance insignificant except for vandalism.

Plant Kills

Certain steps can be taken to preserve vegetation as a necessary part of the cover in the face of potential gas problems.[78] Shallow-rooted species adapt better over anaerobic conditions. Special efforts should be directed to liming, fertilizing, amending, and mulching as described generally in Section 19. Barriers, slots, and vents should also be considered.

Maintenance/Contingency Plan

Some sort of contingency plan for controlling unexpected gas flowage is recommended in view of the associated risk. Such a plan can be adapted from standard plans recommended elsewhere, provided they are modified as appropriate for local soils and conditions. Periodic inspection should be prescribed as a part of the plan; gas concentration measurements within and below the cover are suggested.

Discontinuities

See the discussion in Section 8 on this topic. Breaks in the cover will provide unplanned exits for gas.

SECTION 10

WATER EROSION CONTROL

When raindrops strike bare soil cover at a high velocity, they shatter soil granules and clods and detach particles. Sheet erosion follows where detached soil particles are transported uniformly downslope. Rill erosion develops in channels only inches in depth when soil particles are detached by concentrated flow and by slumping of undercut sidewalls. The capability of runoff to detach soil increases approximately as the square of the shear stress. Consequently, rill erosion increases with increasing slope and channel length, while sheet erosion continues more uniformly between the rills; relative contributions to total soil loss differ with soil and surface conditions.

THE UNIVERSAL SOIL LOSS EQUATION

The most accurate soil loss prediction tool that is now field-operational is the USDA universal soil loss equation (USLE).[62] This equation has been used for agricultural erosion-control planning for more than a decade in the eastern states and is now also used to a limited extent in the western states, Hawaii, and several foreign countries. Development of the equation has involved the analysis of the records from more than 10,000 plot-years of erosion studies at 42 research stations. The USLE is applicable to soil cover over solid waste with limitations as discussed under USE OF USLE FOR DESIGN.

The USLE provides average soil loss as the product of two quantitative factors (soil-erodibility and rainfall-erosivity) and four qualitative factors. The equation is

$$A = RKLSCP \qquad (16)$$

where A = average soil loss, in tons per acre, for the time period used for factor R (e.g., annual)
R = rainfall and runoff erosivity index
K = soil erodibility factor
L = slope-length factor
S = slope-steepness factor
C = cover/management factor
P = practice factor

Rainfall and Runoff Erosivity Factor R

Factor R in the USLE usually equals the pertinent rainfall erosion index EI and is predictable from meteorological data. For average annual soil loss, R can be obtained from Figure 59; for shorter specific time periods, it is the actual local EI for that period. EI is specifically the product of the maximum 30-minute rainfall intensity I in inches per hour and the rainfall kinetic energy E . The E term has been empirically approximated as

$$E = 916 + 331 \log_{10} i \text{ (ft-tons/acre-in.)} \qquad (17)$$

where i is intensity in inches per hour. A tabulation of values from the equation is also available.[80]

The E of an individual rainstorm can be obtained by dividing the storm into successive increments of essentially uniform intensity, using the equation to compute E of each increment, and then summing. The relation of soil loss to EI is linear; therefore, individual-storm values of EI can be summed to obtain seasonal or refined annual values more representative than the generalizations presented in Figure 59. Nevertheless, the R values in the figure are useful approximations, being computed from 22-year rainfall records (1937-1958) for about 2000 locations fairly uniformly distributed over the states east of the Rocky Mountains. For computation of average annual EI values, continuous records of 20 years or more help to avoid bias from cyclical variations in the rainfall pattern.

The computed EI must be modified to evaluate R for the following two special cases:

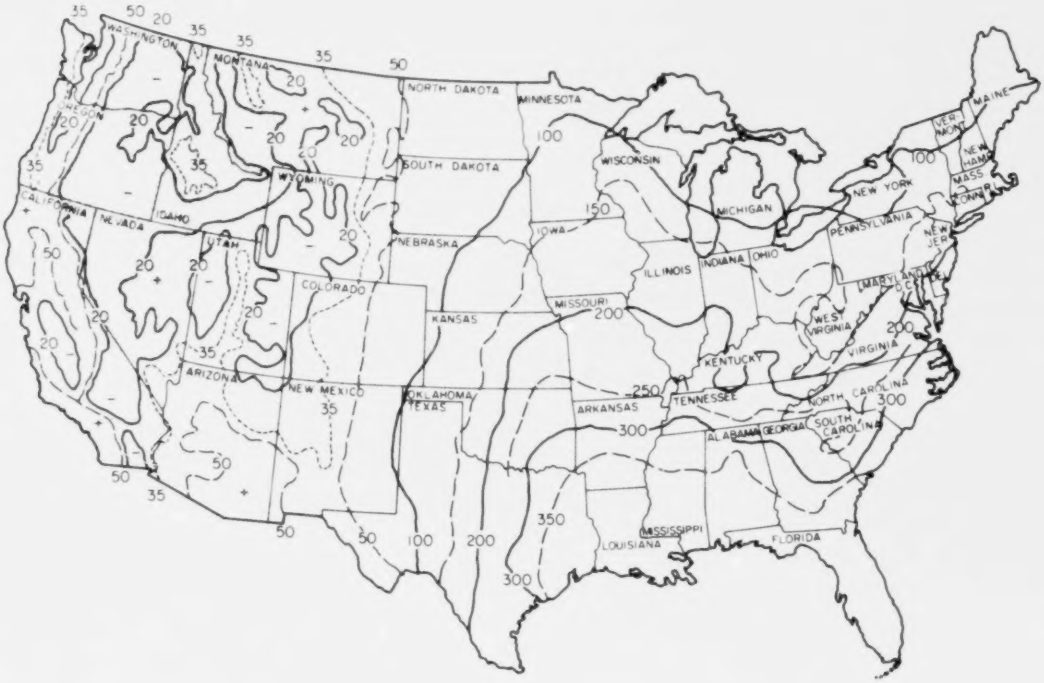

35
50
20
35
35
35
50
WASHINGTON
MONTANA
NORTH DAKOTA
MINNESOTA
MAINE
VERMONT
NEW HAMP
OREGON
20
20
20
20
20
100
100
35
35
SOUTH DAKOTA
WISCONSIN
NEW YORK
MASS
CONN
WYOMING
IDAHO
150
MICHIGAN
CALIFORNIA
NEVADA
UTAH
20
NEBRASKA
IOWA
PENNSYLVANIA
NEW JER
50
20
20
COLORADO
ILLINOIS
INDIANA
OHIO
MARYLAND
D.C.
20
KANSAS
MISSOURI
200
WEST VIRGINIA
200
20
35
VIRGINIA
KENTUCKY
ARIZONA
NEW MEXICO
35
OKLAHOMA
TEXAS
250
TENNESSEE
NORTH CAROLINA
300
ARKANSAS
300
ALABAMA
GEORGIA
SOUTH CAROLINA
50
50
35
350
MISSISSIPPI
LOUISIANA
FLORIDA
50
50
100
200
300

Figure 59. Average annual values of rainfall-erosivity factor R .[79]

a. Where snowmelt runoff on moderate to steep slopes is significant (adjust EI upward).

b. On the Coastal Plains of the Southeast (adjust EI downward). A maximum of 350 has been used temporarily, pending research.

Soil Erodibility Factor K

The average increase in soil loss with increase in EI differs from soil to soil even when rainfall, topography, cover, and management remain the same. The factor K is used to distinguish such differences and is the average soil loss in tons per acre, per unit of R , for a given soil on a "unit plot" (defined as 72.6 ft long with 9 percent slope, continuous fallow, and tilled parallel to the land slope). Long-term plot studies under natural rainfall produced K values ranging from 0.03 to 0.69.

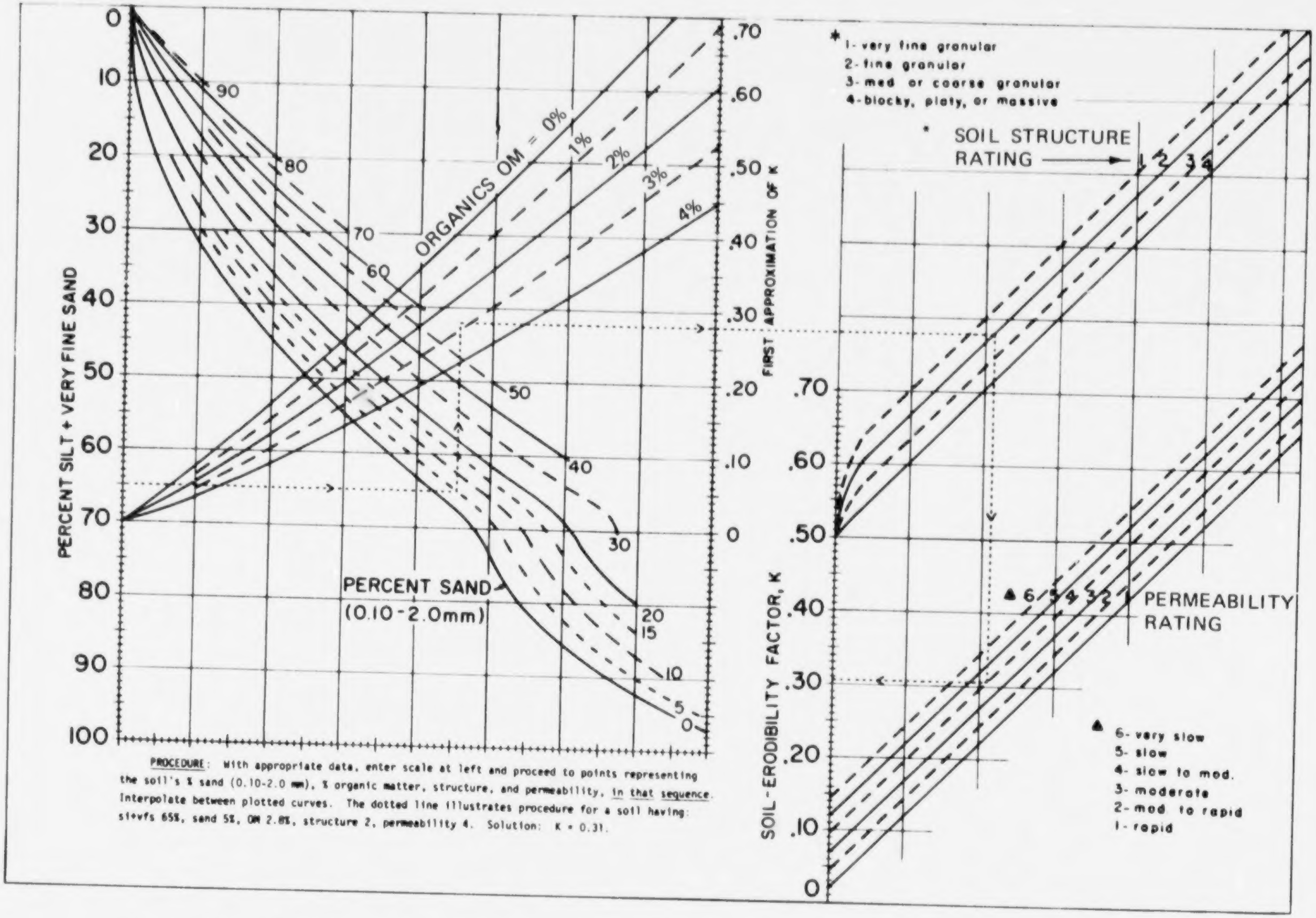
Generally, it has been found that K is affected by particle-size distribution (percent sand, silt, and clay), organic-matter content, soil structure, and permeability. In regard to the grain sizes, very fine sand (0.05-0.10 mm) content is more effectively included with or classified as silt. The nomograph in Figure 60 has been developed from empirical relationships[81] in order to predict K for any soil.

The nomograph solution may be improved in accuracy for some special conditions. Separate K values can be obtained for clays in dry and wet seasons by using, along with normal ratings, increased permeability ratings appropriate for dry, cracked clays in the dry season. Occasionally, one can improve accuracy by regarding loose gravel or rock fragments on the surface as partial mulch cover and reducing the calculated K accordingly. The nomograph has been evaluated as inadequate for distinguishing erodibility of high-clay subsoil (such as excavated and used as solid waste cover); chemical properties of the soil become important here.[82] Standard textural classes (Table 27) are too broad to be accurate indicators of K for in situ agricultural soils but may be useful for first approximations of remolded waste-cover soils.

Topographic Features Factors L and S

The USLE incorporates effects of ground length and steepness in the combined topographic factor LS . The separate factors L and S are the ratios of soil loss in comparison with that from the "unit plot" with length 72.6 ft and slope 9 percent, other conditions remaining constant. The length of concern (Table 28) is from the entry of flow to an exit into a well-defined channel or to a slope decrease sufficient to initiate deposition. The effect of increased length is primarily toward greater accumulation and more channelization of runoff and, in turn, increased erosional capability. Also, runoff tends to increase linearly or greater with increases in steepness, and soil losses increase even more rapidly.

The research data used to derive LS factors in Table 28 were from field plots not longer than 270 ft nor steeper than 18 percent. LS values for greater dimensions and slopes are speculative, being based on extrapolations.



PROCEDURE: With appropriate data, enter scale at left and proceed to points representing the soil's % sand (0.10-2.0 mm), % organic matter, structure, and permeability, in that sequence. Interpolate between plotted curves. The dotted line illustrates procedure for a soil having: si+vfs 65%, sand 5%, OM 2.8%, structure 2, permeability 4. Solution: K = 0.31.

Figure 60. Nomograph for determining soil-erodibility factor K for U. S. Mainland.[79]

TABLE 27. APPROXIMATE VALUES OF FACTOR K FOR USDA TEXTURAL CLASSES[79]

Texture class	Organic matter content <0.5% K	2% K	4% K
Sand	0.05	0.03	0.02
Fine sand	.16	.14	.10
Very fine sand	.42	.36	.28
Loamy sand	.12	.10	.08
Loamy fine sand	.24	.20	.16
Loamy very fine sand	.44	.38	.30
Sandy loam	.27	.24	.19
Fine sandy loam	.35	.30	.24
Very fine sandy loam	.47	.41	.33
Loam	.38	.34	.29
Silt loam	.48	.42	.33
Silt	.60	.52	.42
Sandy clay loam	.27	.25	.21
Clay loam	.28	.25	.21
Silty clay loam	.37	.32	.26
Sandy clay	.14	.13	.12
Silty clay	.25	.23	.19
Clay		0.13-0.29	

The values shown are estimated averages of broad ranges of specific-soil values. When a texture is near the borderline of two texture classes, use the average of the two K values.

Soil loss estimates for slopes steeper than about 30 percent are potentially subject to considerable error.

Shape of the slope is also important. An irregular slope can be evaluated as a series of segments with uniform gradients. For engineered landfills, two or three segments should be sufficient. Provided the segments are selected so that they are also of equal length, Table 28 can be used with certain adjustments that have been found[62] to be appropriate. Enter Table 28 with the total slope length for LS values corresponding to the percent slope of each segment. For three segments, multiply the chart LS values for the upper, middle, and lower segments by 0.58, 1.06, and 1.37, respectively. The average of the three products is a good estimate of the overall effective LS value. If two segments are sufficient, use the multiples 0.71 and 1.29.

TABLE 28. VALUES OF THE FACTOR LS FOR SPECIFIC COMBINATIONS OF SLOPE LENGTH AND STEEPNESS[79]

% Slope	Slope length (feet)											
	25	50	75	100	150	200	300	400	500	600	800	1000
0.5	0.07	0.08	0.09	0.10	0.11	0.12	0.14	0.15	0.16	0.17	0.19	0.20
1	0.09	0.10	0.12	0.13	0.15	0.16	0.18	0.20	0.21	0.22	0.24	0.26
2	0.13	0.16	0.19	0.20	0.23	0.25	0.28	0.31	0.33	0.34	0.38	0.40
3	0.19	0.23	0.26	0.29	0.33	0.35	0.40	0.44	0.47	0.49	0.54	0.57
4	0.23	0.30	0.36	0.40	0.47	0.53	0.62	0.70	0.76	0.82	0.92	1.0
5	0.27	0.38	0.46	0.54	0.66	0.76	0.93	1.1	1.2	1.3	1.5	1.7
6	0.34	0.48	0.58	0.67	0.82	0.95	1.2	1.4	1.5	1.7	1.9	2.1
8	0.50	0.70	0.86	0.99	1.2	1.4	1.7	2.0	2.2	2.4	2.8	3.1
10	0.69	0.97	1.2	1.4	1.7	1.9	2.4	2.7	3.1	3.4	3.9	4.3
12	0.90	1.3	1.6	1.8	2.2	2.6	3.1	3.6	4.0	4.4	5.1	5.7
14	1.2	1.6	2.0	2.3	2.8	3.3	4.0	4.6	5.1	5.6	6.5	7.3
16	1.4	2.0	2.5	2.8	3.5	4.0	4.9	5.7	6.4	7.0	8.0	9.0
18	1.7	2.4	3.0	3.4	4.2	4.9	6.0	6.9	7.7	8.4	9.7	11.0
20	2.0	2.9	3.5	4.1	5.0	5.8	7.1	8.2	9.1	10.0	12.0	13.0
25	3.0	4.2	5.1	5.9	7.2	8.3	10.0	12.0	13.0	14.0	17.0	19.0
30	4.0	5.6	6.9	8.0	9.7	11.0	14.0	16.0	18.0	20.0	23.0	25.0
40	6.3	9.0	11.0	13.0	16.0	18.0	22.0	25.0	28.0	31.0	--	--
50	8.9	13.0	15.0	18.0	22.0	25.0	31.0	--	--	--	--	--
60	12.0	16.0	20.0	23.0	28.0	--	--	--	--	--	--	--

Values given for slopes longer than **300** feet or steeper than **18%** are extrapolations beyond the range of the research data and, therefore, less certain than the others.

Cover/Management Factor C

Factor C in the USLE is the ratio of soil loss from land cropped under specified conditions to that from clean-tilled, continuous fallow.[62] Therefore, C combines effects of vegetation, crop sequence, management, and agricultural (as opposed to engineering) erosion-control practices. On landfills, freshly covered and without vegetation or special erosion-reducing procedures of cover placement, C will usually be about unity. Where there is vegetative cover or significant amounts of gravel, roots, or plant residues or where cultural practices increase infiltration and reduce runoff-velocity, C is much less than unity. C ranges from about 0.60 to less than 0.01 on cropped land and, therefore, is important to planning erosion control on landfill.

A field-tested routine adaptable to landfill planning modifies C to reflect the net effect of interrelated crop and management variables and local rainfall patterns or seasons. The first-year procedure amounts to distinguishing five crop stages: cover placement (rough fallow), seedling, establishment, developing-maturing crop, and sometimes residue-stubble. Probable calendar dates for successive periods are selected. The fraction of the local annual EI that normally occurs during each crop stage is next estimated. These fractions are multiplied by estimated corresponding C values (Table 29), and the resulting products are summed to obtain the overall C .

In the second and subsequent years, the cover placement, seedling, and establishment stages are not normally repeated, and C values should be summed from developing-maturing and possibly residual-stubble stages only. Computed C values are in many cases available upon request from local SCS offices.

Supporting Practices Factor P

Factor P in the USLE is similar to C , except that it accounts for additional effects of practices that are superimposed on the cultural practices, e.g., contouring, terracing, and contour stripcropping. Approximate values of P , related only to slope steepness, are listed in Table 30. These values are based on rather limited field data, but P has a narrower range of possible values than the other five factors. Influences of the type of vegetation, residue management, rainstorm characteristics, and soil properties on the value of P have not been evaluated to the point of predictability.

COVER CONSTRUCTION FACTORS

Several construction factors complicate the picture developed by the USLE as follows.

Compaction Effects

The effect of compaction on soil erodibility is not well understood. Numerous researchers have considered the question[83-85] but seem to have produced conflicting results. One study, unfortunately of limited scope, obtained the results presented in Figure 61. The dry unit weight at which a cohesive soil is most susceptible to erosive breakdown was indicated to vary with variation in slope, other factors remaining constant. For the ML soil at 1V on 1H, the greatest erosion occurred when the soil was heavily compacted; but at slopes of only 1V on 3H, the greatest erosion occurred when the soil was lightly compacted. At intermediate slopes, the critical unit weight was suggested to lie somewhere between. This study taken alone seems to indicate that on solid waste sites where long slopes seldom exceed 1V on 3H, the more the compaction, the less the erosion, within practical limits.

Blending Effects

Composite soils are seldom prepared primarily for erosion resistance; nevertheless, several conclusions are considered pertinent on the assumption that mixing of separate soil components is a viable cover option in special cases. The following are generalizations[86] on composition effects of compacted soils. Erodibility generally increases with:

a. Increasing silt content.

b. Decreasing clay content.

TABLE 29. GENERALIZED VALUES OF FACTOR C FOR STATES EAST OF THE ROCKY MOUNTAINS[79]

Crop, rotation, and management	Productivity level	
	High	Mod.
	C value	
Base value: continuous fallow, tilled up and down slope	1.00	1.00
CORN		
C, RdR, fall TP, conv	0.54	0.62
C, RdR, spring TP, conv	.50	.59
C, RdL, fall TP, conv	.42	.52
C, RdR, wc seeding, spring TP, conv	.40	.49
C, RdL, standing, spring TP, conv	.38	.48
C-W-M-M, RdL, TP for C, disk for W	.039	.074
C-W-M-M-M, RdL, TP for C, disk for W	.032	.061
C, no-till pl in c-k sod, 95-80% rc	.017	.053
COTTON		
Cot, conv (Western Plains)	0.42	0.49
Cot, conv (South)	.34	.40
MEADOW		
Grass & Legume mix	0.004	0.01
Alfalfa, lespedeza or Sericia	.020	
Sweet clover	.025	
SORGHUM, GRAIN (Western Plains)		
RdL, spring TP, conv	0.43	0.53
No-till pl in shredded 70-50% rc	.11	.18
SOYBEANS		
B, RdL, spring TP, conv	0.48	0.54
C-B, TP annually, conv	.43	.51
B, no-till pl	.22	.28
C-B, no-till pl, fall shred C stalks	.18	.22
WHEAT		
W-F, fall TP after W	0.38	
W-F, stubble mulch, 500 lbs rc	.32	
W-F, stubble mulch, 1000 lbs rc	.21	

Abbreviations defined:

B	soybeans
C	corn
c-k	chemically killed
conv	conventional
cot	cotton
F	fallow
M	grass & legume hay
pl	plant
W	wheat
wc	winter cover
lbs rc	pounds of crop residue per acre remaining on surface after new crop seeding
% rc	percentage of soil surface covered by residue mulch after new crop seeding
70-50% rc	70% cover for C values in first column; 50% for second column
RdR	residues (corn stover, straw, etc.) removed or burned
RdL	all residues left on field (on surface or incorporated)
TP	turn plowed (upper 5 or more inches of soil inverted, covering residues)

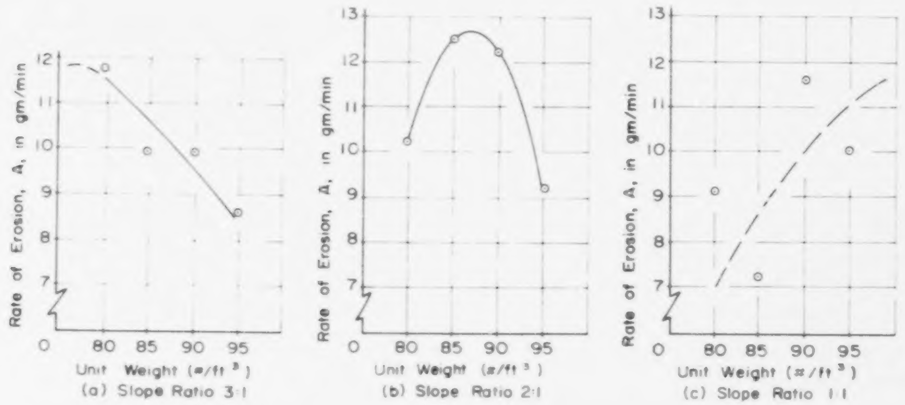
TABLE 30. VALUES OF FACTOR P[79]

Practice	Land slope (percent)				
	1.1-2	2.1-7	7.1-12	12.1-18	18.1-24
	(Factor P)				
Contouring (P_c)	0.60	0.50	0.60	0.80	0.90
Contour strip cropping (P_{sc})					
R-R-M-M[1]	0.30	0.25	0.30	0.40	0.45
R-W-M-M	0.30	0.25	0.30	0.40	0.45
R-R-W-M	0.45	0.38	0.45	0.60	0.68
R-W	0.52	0.44	0.52	0.70	0.90
R-O	0.60	0.50	0.60	0.80	0.90
Contour listing or ridge planting (P_{cl})	0.30	0.25	0.30	0.40	0.45
Contour terracing (P_t)[2]	[3] $0.6/\sqrt{n}$	$0.5/\sqrt{n}$	$0.6/\sqrt{n}$	$0.8/\sqrt{n}$	$0.9/\sqrt{n}$
No support practice	1.0	1.0	1.0	1.0	1.0

[1] R = rowcrop, W = fall-seeded grain, O = spring-seeded grain, M = meadow. The crops are grown in rotation and so arranged on the field that rowcrop strips are always separated by a meadow or winter-grain strip.

[2] These P_t values estimate the amount of soil eroded to the terrace channels and are used for conservation planning. For prediction of off-field sediment, the P_t values are multiplied by 0.2.

[3] n = number of approximately equal-length intervals into which the field slope is divided by the terraces. Tillage operations must be parallel to the terraces.



(a) Slope Ratio 3:1

(b) Slope Ratio 2:1

(c) Slope Ratio 1:1

Figure 61. Effect of unit weight on erosion rate at three different slopes.[83] Soil is classified ML. (Reproduced by permission of American Society of Civil Engineers.)

c. Increasing amount of organic material in sandy soils.

d. Decreasing amount of organic material in clayey soils.

e. Decreasing plasticity index.

The overall effect of sand content is less definite, since sand grains are easily detached by splash erosion but are transported with relatively greater difficulty than fines.

Stabilization with Additives and Cements*

Numerous agents for general stabilization and against water erosion are listed in Table 10.* Cement-stabilized soils are used occasionally for lining embankments and drainage ditches. Oil-in-water emulsions have been used on a large scale, despite limited water resistance of some, since their resinous petroleum fractions have strong affinity to soils. One study[87] has indicated the following order of decreasing effectiveness of selected additives: water soluble urethane, vinyl acetate emulsion, synthetic rubber latex, and acrylic ester emulsion. Erosion resistance tests of several petrochemical additives, using water jet erosion,[88] showed the most effective were Peneprime, Airflex 720, Dowell M145, Aerospray 52 and 70, Geotech stabilizer EA-11-004, and 1:1 mixture of Geotech stabilizer SA-117-58 and Surface stabilizer. In another study,[89] spray-on chemicals effective in controlling erosion of uncemented sand were Soilbond, Landlock, Curasol AH, and Aerospray 70, but the traditional method of rolled-in straw and sprayed-on fiber was, in general, the most effective and least expensive method of erosion control.

Aerospray 70 and Curasol AH performed best on highly erodible Piedmont regional soils[90] but did not perform as well as the straw-emulsion method. In the moderately erodible soils of the Ridge and Valley region, Petroset SB and Soilgard were best. The Atlantic Coastal Plain's slightly erodible soils performed well with Petroset SB and asphalt emulsion. None of the chemicals tested were as cost-effective as the conventional mixture of straw and asphalt-emulsion (see Section 19).

From laboratory tests to evaluate 70 chemicals used in erosion control on tailings ponds,[91] effective additives were ranked in order of decreasing cost-effectiveness as lignosulfonates, Compound SP-400, Soilgard, DCA-70, cement and lime, sodium silicates, Paracol TC-1842, Pamak WTP, Petroset SB-1, PB-4601, Rezosol, Dresinol TC-1843, Coherex, and potassium silicate.

Mulching Effects

Mulch or crop residue effectively protects cropland during the approximately 8 months from harvest until the next crop develops. A similar effect is expected where mulch is placed on solid waste cover. Figure 62 shows the average relation of soil loss to variations in mulch coverage, as observed on

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* The additives and cements listed in Table 10 and those discussed here are from separate sources and have not been interrelated.

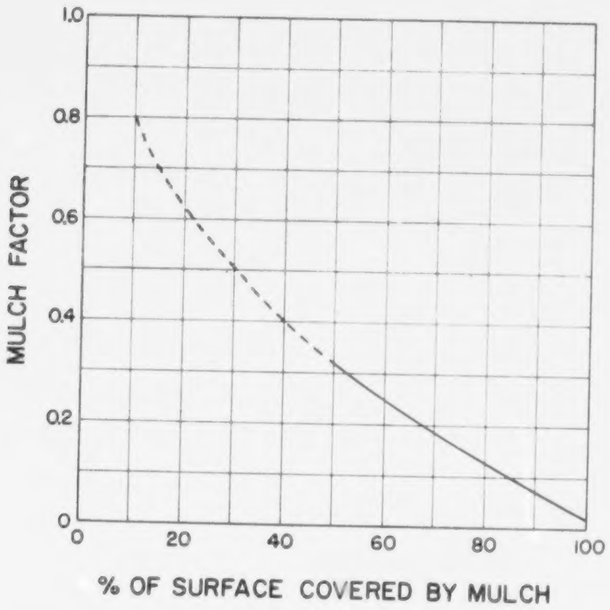


Figure 62. Effect of plant-residue mulch on soil loss.[62] Mulch factor is soil loss with mulch divided by soil loss without mulch.

35-ft cropland slopes subjected to 5 in. of simulated rain in two 1-hour storms. The mulch factor approximates the ratio of loss with mulch to loss without. How much the slope length or steepness could be increased before unanchored mulch would be undercut or transported by the flowing water has, however, not been fully determined. The relative effectiveness of several types of mulch and related surface additions is indicated in Figure 63 for a rain intensity of 2.5 in./hr to a total of 5 in.[92] See Section 19 for discussion of various mulch types.

Special Drainage Features

Surface drainage helps to remove water as surface runoff before it can infiltrate the cover and enter the solid waste cells in an uncontrolled manner. A well-organized system of ditches and laterals is often essential, and a source, such as Reference 36, may be needed for particulars. The design of the system, however, must also incorporate accessories that assure an acceptably low level of erosion during fast runoff. Some drainage accessories are illustrated in Figures 64 and 65 for consideration in reducing erosion in ditches; berms and ditch linings for direct protection; check dams for reducing velocity and in turn scouring; and spillways to carry concentrated flow off the steep edges of a disposal area. Another option is to adjust design to wider and shallower channel cross sections in order to reduce velocity (Figure 66). A flat-bottomed channel is considered best.

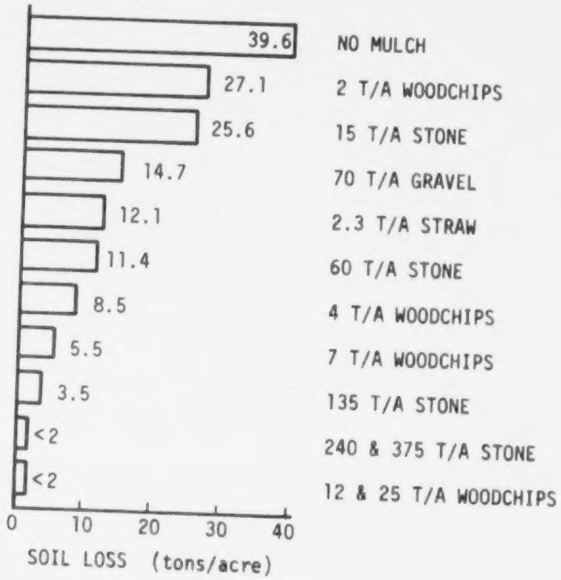


Figure 63. Influence of mulch types on rates of soil loss from 5H on 1V construction slope.[92]

USE OF USLE FOR DESIGN

Considerable design control can be exerted on erosion of cover at a solid waste disposal area on the basis of the USLE. Specific controls may take the form of restrictions on the choice of cover soil, or on the various design features for drainage, top and side slopes, and surface treatment or vegetation. A particularly useful technique in selecting appropriate soil is with the erodibility factor K . The only precaution here is that site selection studies should be adequate to quantify the characteristics needed for analysis of remolded soil mixtures for the landfill cover as distinct from tilled cropland soils. It is also critical in using the USLE, which was developed for agricultural purposes, that allowance be made for distinctions of landfill cover/management practices.

The USLE is useful for comparing effectiveness of optional cover soils or for evaluating proposed cover against specific allowable erosion soil loss. Where a limiting loss, e.g., in tons per acre per unit time, is specified, a proposed cover type and configuration, rainfall pattern, and cover management and practice can be quickly evaluated for acceptability using Equation 16. This approach should prove useful in many cases, if not in most, since the climate is fixed, the choice of soil type may be rather inflexible, and consequently, the equation is simplified considerably.

Elsewhere, the designing of cover for small landfills may reduce to choosing among a few established standard configurations rather than being a result of engineering analysis. The USLE, in this circumstance, can quickly rank the optional designs according to effectiveness in erosion control.

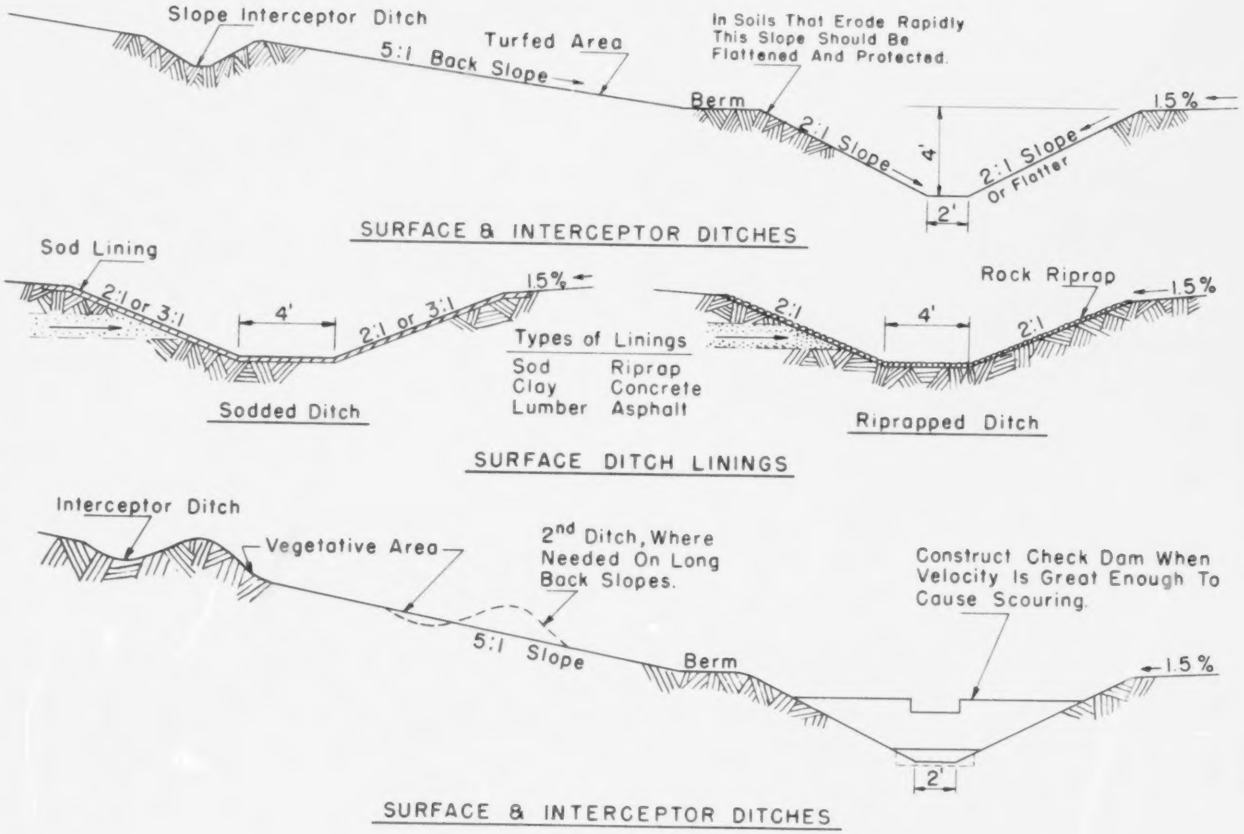

Slope Interceptor Ditch
Turfed Area
5:1 Back Slope
In Soils That Erode Rapidly This Slope Should Be Flattened And Protected.
Berm
2:1 Slope
4'
2:1 Slope Or Flatter
1.5%
2'
SURFACE & INTERCEPTOR DITCHES
Sod Lining
2:1 or 3:1
4'
2:1 or 3:1
1.5%
Sodded Ditch
Types of Linings
Sod
Clay
Lumber
Riprap
Concrete
Asphalt
2:1
4'
2:1
Rock Riprap
1.5%
Riprapped Ditch
SURFACE DITCH LININGS
Interceptor Ditch
Vegetative Area
2nd Ditch, Where Needed On Long Back Slopes.
5:1 Slope
Berm
Construct Check Dam When Velocity Is Great Enough To Cause Scouring.
1.5%
2'
SURFACE & INTERCEPTOR DITCHES

Figure 64. Surface and interceptor ditches.

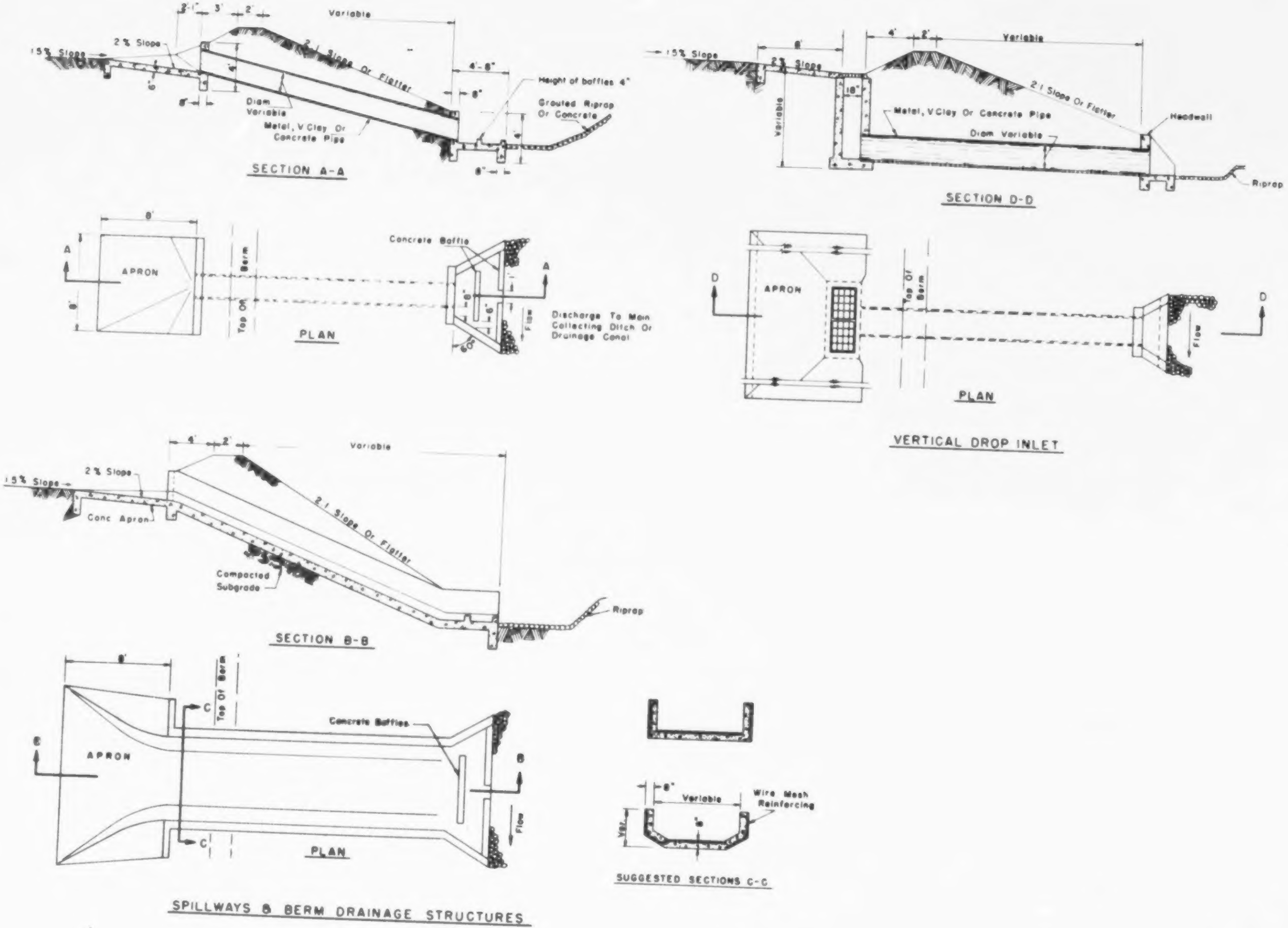

15% Slope
2% Slope
Variable
2:1 Slope Or Flatter
Height of baffles 4"
Grouted Riprap Or Concrete
Diam Variable
Metal, V Clay Or Concrete Pipe
SECTION A-A
APRON
Top Of Berm
Concrete Baffle
Discharge To Main Collecting Ditch Or Drainage Canal
Flow
PLAN
Headwall
Riprap
SECTION D-D
PLAN
VERTICAL DROP INLET
Conc Apron
Compacted Subgrade
SECTION B-B
Concrete Baffles
PLAN
Wire Mesh Reinforcing
SUGGESTED SECTIONS C-C
SPILLWAYS & BERM DRAINAGE STRUCTURES

Figure 65. Embankment protection structures.

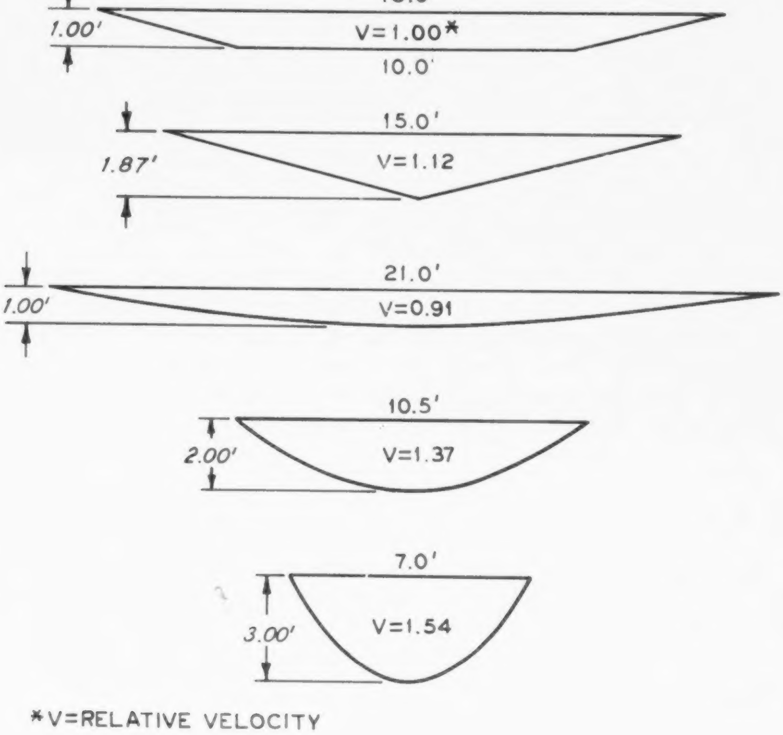


Figure 66. Effect of drainage ditch shape on velocity and erosivity.

DESIGNING FOR WATER EROSION CONTROL

Several approaches are available to the designer of landfill cover for minimizing water erosion. Also, see Reference 72 for useful details on erosion control in grounds maintenance.

Selection of Erosion-resistant Soils

The nomograph of Figure 60 provides the direct means of ranking specific available soils for erosion-resistance and providing K-values for quantification. In this selection process, the other major USLE factors are independent of variations in K and need not be considered. For purposes of covering solid waste, the variables in the nomograph are probably reduced from their original importance in agriculture by virtue of the remolding and mixing during cover-soil excavation and placement. Therefore, the K values in Table 27, based largely on grain size, are probably representative, and the table may be considered as a simple alternate or for checking Figure 60 values.

Dispersive Clay and Dispersants

Soils in a dispersed condition as a result of intrinsic nature or chemical treatments are usually susceptible to excessive erosion. Such materials should be avoided where erosion is of importance. The SCS has considerable experience with recognizing and handling local, dispersive clay and may be able to give advice on potential problems.

Overall Landfill Configuration

The two factors, L and S in the USLE, dominate the erosion aspect of runoff. For relatively small to intermediate size disposal areas (<500 ft across), L is ordinarily subordinate to S , and a favorable configuration is largely determined by suitably gentle slopes. Table 28 indicates that S can be held below 0.2 (an arbitrary limit for example) only on nearly flat slopes. As a rule of thumb, try to hold overall top slope to 5 percent or less.

Drainage Features

Ditches may be stabilized with vegetation, additives, linings, or berms. Also consider using special features as shown in Figures 64 and 65. Channel bottom width can be increased to reduce velocity.

External Runoff Diversion

It is generally essential to divert natural drainage from outside the immediate site from overflowing the solid waste cover. This diversion can be accomplished easily by maintaining throughout construction an adequate ditch along the hillside near the intermittently changing boundary of cut or original ground surface to landfill surface. The landfill, being located on the vulnerable, downhill side, may require a soil berm as erosion protection where heavy natural flow is anticipated.

Any cut more than 5 ft high with higher ground above should be provided with a cutoff ditch several feet back of the top-of-cut line to intercept surface water flowing down from the higher ground. Placing a ditch at the base of the cut is also good practice. The cut slope may be protected further by riprap, sod, or temporary mulch.

Side Slope Protection

Important final fill slopes more than 5 ft high should be protected from erosion by building berms and gutters along the top of the slope. The surface water, thus intercepted, may be disposed of by spillways and vertical drop inlets or other suitable conduits to proper outfall ditches. Methods of protecting fill slope berms include shooting with light asphaltic material, paving with sod, or providing paved gutters.

Favorable Cropping Practices

The importance of vegetation in reducing erosion was emphasized under

Cover/Management Factor C. Vegetation should be started as soon as possible on final cover, in some cases cell by cell. It may even be feasible to seed intermediate cover soils for the benefits the roots and canopy will bring over a single season. Tables 29 and 30 summarize the relative effectiveness of various vegetation-based agricultural practices in reducing erosion.

Application of Mulch

The use of mulch or inert materials is often specified to minimize exposure and protect otherwise bare soil at construction sites. Figures 62 and 63 provide guidance on the various types of mulch. Applications should always be encouraged for the interval before vegetation emerges.

Smoothing and Compaction

The principal reason for smoothing and compacting cover soil is for the desired effects on control of water and gas movement (Section 8). However, the compaction also has effects on erosion (see COVER CONSTRUCTION FACTORS), and this aspect should be considered, too. It appears that special compactive effort is beneficial in reducing erosion (except on steep slopes) and at the same time helps control infiltration. Therefore, a program of compaction of final and sometimes intermediate and daily cover is recommended as explained in Section 5.

Additives

According to the experiences cited under Stabilization with Additives and Cements, cement and several chemical stabilizers are effective against soil erosion. However, generally the most cost-effective method of erosion control, until natural grass cover is established, is the straw-mulch treatment, either rolled into the soil or sprayed with asphalt emulsion.

Maintenance

The need for considering long-term maintenance to avoid erosion problems is discussed in DESIGNING FOR FUTURE USE in Section 22.

SECTION 11

WIND EROSION CONTROL

Wind erosion of agricultural lands is a serious problem in arid and semi-arid regions and elsewhere on sandy soils as witnessed by the Dust Bowl of the southern Great Plains (Figure 67). Published information on wind forces that can be used for predicting wind erosion and for designing control practices is not abundant. However, sufficient data have been assembled within the past 35 years to allow characterization of wind forces at specific stations (Table 31) and generalization of these characteristics to encompassing regions for use in design.

This section follows a procedure[93] for using wind characteristics along with soil and vegetation factors found to be important in the erosion process to predict soil loss and as a basis for designing erosion control measures. An earlier, simpler exponential equation[94] expressed the amount of soil loss as a function of soil cloddiness or grain size, amount of surface vegetation residue, and degree of surface roughness.

EROSION IN THE SOLID WASTE/SOIL SYSTEM

The majority of studies on wind erosion and measures for its reduction have been conducted in the interest of agriculture. The seriousness of wind erosion is obvious on this scale where plowed fields may be thousands of feet across and extending together over large regions. Correspondingly, the erosion potential at landfills is of much lesser magnitude. Another aspect of erosion may arise on landfills (particularly inactive landfills) where the cover of soil is actually breached by erosion to expose the waste to potential wind dispersion. Such small, localized instances of wind erosion are of potentially widespread concern.

Besides having the obvious advantage in small size and, in turn, reduced problem magnitude, the landfill is distinct in other basic ways. The landfill is subject to design, wherein overall configuration, orientation, and composition of the cover can be manipulated to reduce erosion potential. One problem to be faced in covering solid waste is the thoroughly remolded condition of the soil and its reduced erosion resistance after excavation. Also, landfill equipment tends to be heavy (in comparison with farm equipment) and to make numerous traverses, and the grain or clod size is reduced further in this additional intense reworking. In the process of effective grain-size reduction, the cover soil becomes more erodible. This aspect is not covered in the following prediction equation and should be carefully considered separately.

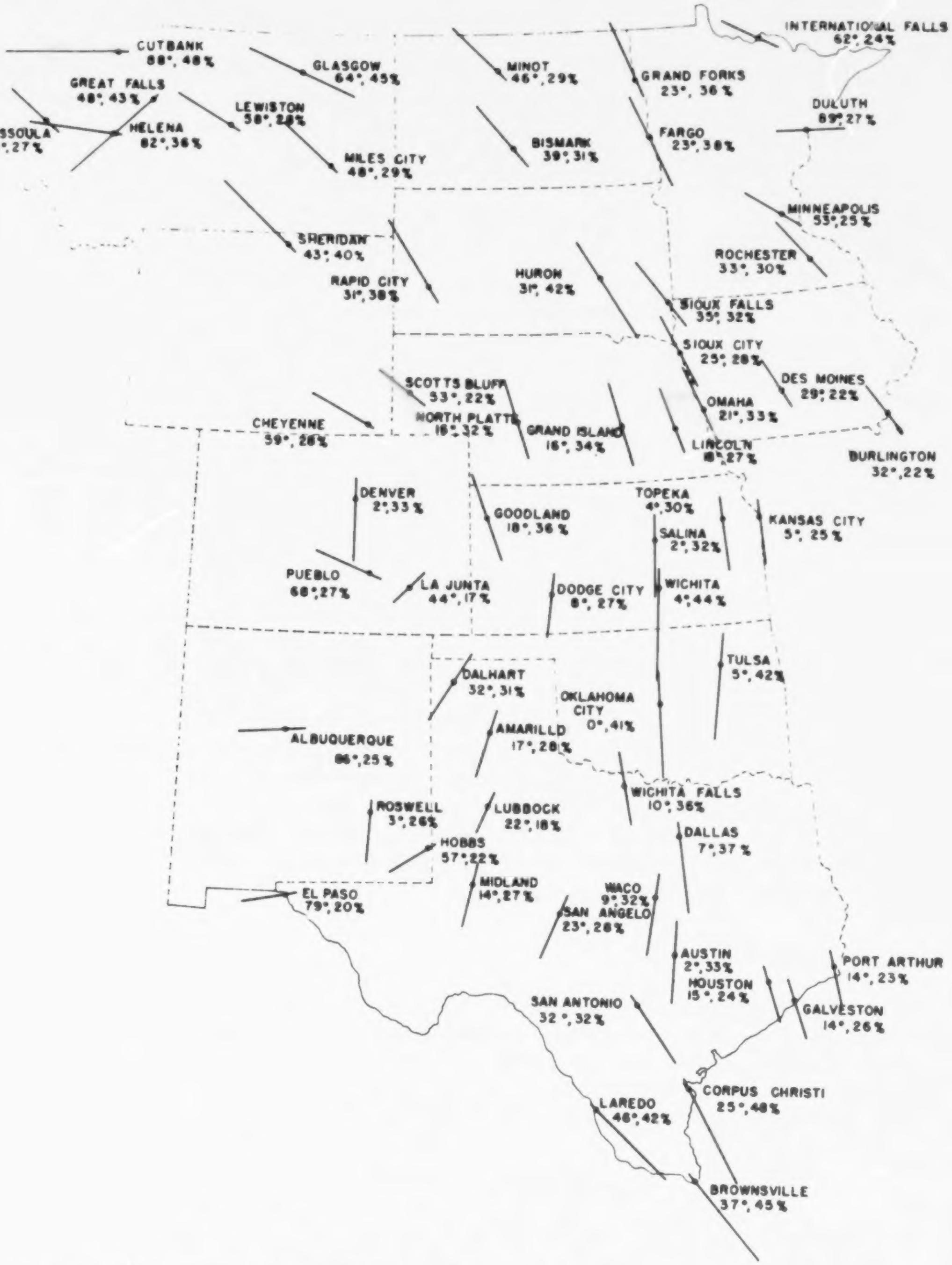

CUTBANK
88°, 48%
GLASGOW
64°, 45%
GREAT FALLS
48°, 43%
LEWISTON
58°, 28%
MISSOULA
51°, 27%
HELENA
82°, 36%
MILES CITY
48°, 29%
SHERIDAN
43°, 40%
RAPID CITY
31°, 38%
MINOT
46°, 29%
BISMARK
39°, 31%
GRAND FORKS
23°, 36%
FARGO
23°, 38%
INTERNATIONAL FALLS
62°, 24%
DULUTH
89°, 27%
MINNEAPOLIS
53°, 25%
ROCHESTER
33°, 30%
HURON
31°, 42%
SIOUX FALLS
35°, 32%
SIOUX CITY
25°, 28%
DES MOINES
29°, 22%
SCOTTS BLUFF
53°, 22%
NORTH PLATTE
16°, 32%
CHEYENNE
59°, 26%
GRAND ISLAND
16°, 34%
OMAHA
21°, 33%
LINCOLN
18°, 27%
BURLINGTON
32°, 22%
DENVER
2°, 33%
GOODLAND
18°, 36%
TOPEKA
4°, 30%
SALINA
2°, 32%
KANSAS CITY
5°, 25%
PUEBLO
68°, 27%
LA JUNTA
44°, 17%
DODGE CITY
8°, 27%
WICHITA
4°, 44%
TULSA
5°, 42%
DALHART
32°, 31%
OKLAHOMA
CITY
0°, 41%
ALBUQUERQUE
86°, 25%
AMARILLO
17°, 28%
WICHITA FALLS
10°, 36%
ROSWELL
3°, 26%
LUBBOCK
22°, 18%
DALLAS
7°, 37%
HOBBS
57°, 22%
MIDLAND
14°, 27%
WACO
9°, 32%
SAN ANGELO
23°, 28%
EL PASO
79°, 20%
AUSTIN
2°, 33%
PORT ARTHUR
14°, 23%
HOUSTON
15°, 24%
SAN ANTONIO
32°, 32%
GALVESTON
14°, 26%
CORPUS CHRISTI
25°, 48%
LAREDO
48°, 42%
BROWNSVILLE
37°, 45%

Figure 67. Prevailing wind erosion direction in the Great Plains showing degrees from north or south and percentage of all erosion occurring along that direction.95 (Reproduced by permission of Soil Science Society of America.)

TABLE 31. EXAMPLE OF MONTHLY WIND CHARACTERISTICS* AVAILABLE FOR U. S. STATIONS[93]

Item	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Laredo, Tex. (Jan. 1943 – Feb. 1945; Sept. 1946 – Aug. 1955)												
Magnitude	175	222	320	409	437	496	433	357	240	228	196	169
Direction	115	135	135	135	135	135	135	135	135	135	113	113
Preponderance	1.9	1.8	1.7	2.4	2.9	3.5	3.8	3.2	1.7	2.2	1.8	2.0
Lubbock, Tex. (Aug. 1942 – Dec. 1945; Jan. 1950 – Dec. 1956)												
Magnitude	308	438	640	546	456	428	178	145	209	204	293	385
Direction	43	23	22	45	68	90	90	90	68	67	56	22
Preponderance	1.3	1.2	1.5	1.1	1.3	1.9	2.0	1.5	2.0	1.6	1.2	1.2
Midland, Tex. (Apr. 1940 – Oct. 1946)												
Magnitude	141	262	346	455	289	245	118	95	149	150	143	166
Direction	23	180	45	157	90	90	90	90	90	90	45	90
Preponderance	1.6	1.1	1.2	1.1	1.5	1.8	1.7	1.5	1.8	1.9	1.4	1.1
Port Arthur, Tex. (May 1950 – Apr. 1955)												
Magnitude	359	393	386	379	265	149	171	76	97	149	252	320
Direction	135	90	90	112	112	90	90	68	67	112	112	112
Preponderance	1.5	1.6	2.2	2.1	2.3	1.6	1.2	1.3	1.3	1.3	1.4	1.4

* Characteristics are defined as follows: Magnitude - sum of the products of the cube of mean windspeed greater than 12 mph times wind duration for all 16 principal compass directions; direction - angle in degrees parallel to maximum wind erosion direction, measured counterclockwise with east 0°, north 90°, west 180°, and south 270°; preponderance - ratio of wind erosion forces, parallel force: perpendicular force.

THE WIND EROSION EQUATION

Soil loss depends on cloddiness, surface roughness, and surface moisture of the soil; on amount, kind, and orientation of the vegetation; on wind velocity or force; and on the windward distance across the field. The wind erosion equation (WEE) expresses functionally the amount of erosion, in tons per acre per annum, from a given soil surface as

$$A' = f(K', C', L', T', V')^{*} \tag{18}$$

---

* To avoid confusion with other symbols in this report, it has been necessary to change some symbols from the source references, e.g., K' in place of the original I' .

where K' = a soil erodibility index
T' = a soil ridge roughness factor
C' = a climatic factor
L' = the field length along the prevailing wind erosion direction
V' = an equivalent quantity of vegetative cover

Climatic Factor C'

The climatic factor C' combines two important aspects of the erosion process--wind velocity v and near-surface water content w . An empirical relation[95] indicates that C' is approximately proportional to v^3/w^2 . C' in percent has been calculated[93] for most regions of the United States on an average monthly basis (e.g., Figure 68). Wind speeds below 13 mph are indicated by experimentation to be nonerosive.

The WEE was originally set up in terms of C' averaged annually to account for annual soil loss. As subsequently expanded[93] to obtain monthly erosion losses using monthly C' (Figure 68), the equation may require considerable judgment as to what climatic conditions (which months) account for most erosion. Until clarified by further research, it seems best to use the monthly C' factor and procedure[93] outlined below to estimate monthly erosion loss and to regard these estimates as highly conservative (excessively large amounts).

Soil Erodibility K'

Soil erodibility K' includes the second most important aspect of the erosion process, the nature of the soil, and also an adjustment for knoll or hill configuration. K' is equal to the product of the soil erodibility factor from Figure 69 and the knoll adjustment available in Figure 70. The important effect of soil grain or clod size is clearly evident in the figure.

Soil Ridge Roughness Factor T'

Soil ridge roughness is a measure of the surface roughness other than caused by clods or vegetation.[95] It is determined from direct observations and given in terms of the actual amplitude measurement from crest to trough in the ground microtopography. The effect of the roughness on wind erosion is incorporated as a percentage factor T' obtained from Figure 71. The figure shows that roughness of about 3- to 4-in. depth has the maximum reducing effect on erosion.

Field Length Factor L'

The equivalent field length L' is defined as the unsheltered distance along the direction of prevailing wind erosion (Figure 67). L' is obtained by measuring the distance across the landfill exposure and subtracting lengths protected by barriers, such as hedges and thick fences. Barrier protection is usually estimated at 10 times the barrier height where a better length determination is lacking. L' is not applied directly in the WEE but is instead used in a graphical procedure (Figure 72) as explained under USE OF WEE FOR DESIGN.

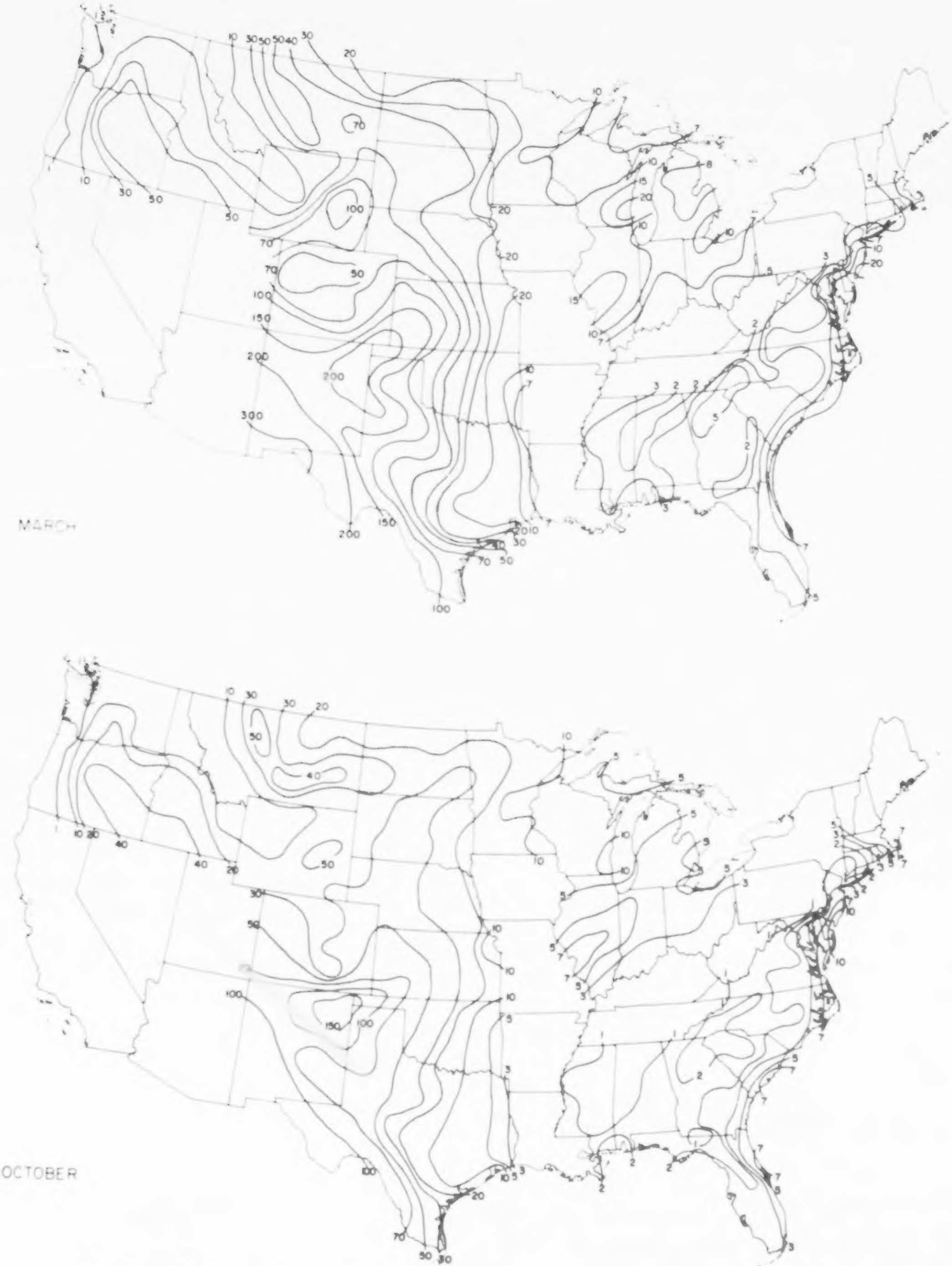

MARCH
10
30
50
70
100
150
200
300
20
OCTOBER
10
20
40
50
100
150

Figure 68. Wind erosion climatic factor C' in percent for March and October.93

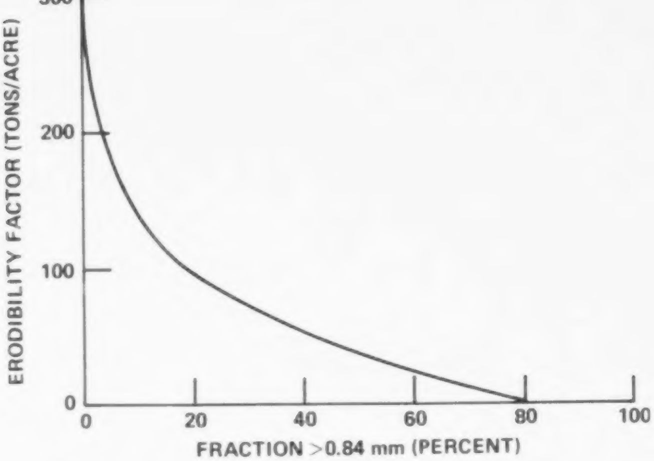


Figure 69. Wind erosion versus percent coarse fraction.[93]

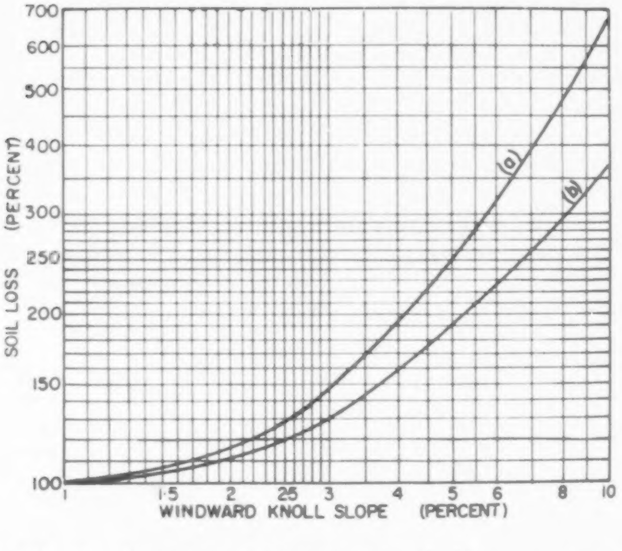


Figure 70. Knoll adjustment (a) from top of knoll and (b) from upper third of slope.[95] (Reproduced by permission of Soil Science Society of America.)

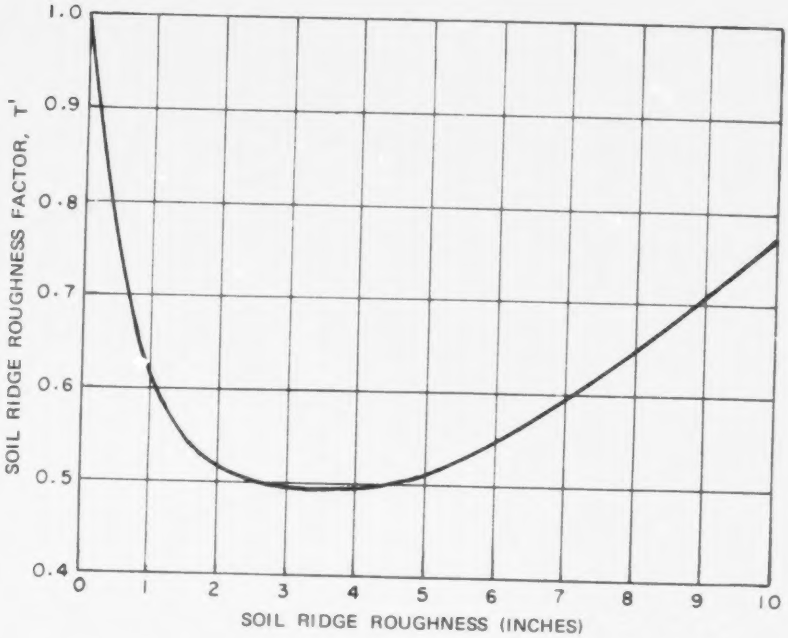


Figure 71. Soil ridge roughness factor T' from actual soil ridge roughness.93

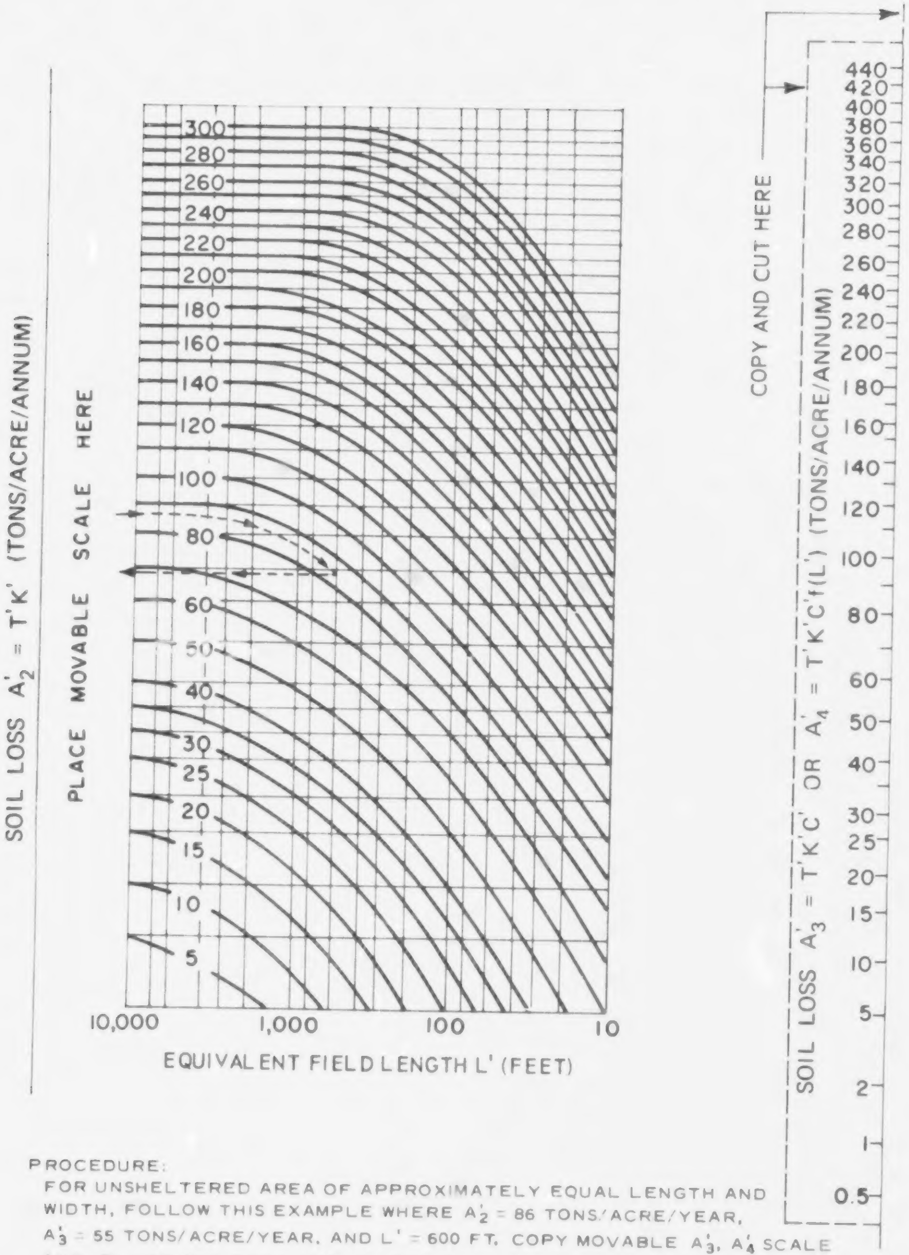
Vegetative Cover Quantity V'

The vegetative cover quantity V' combines type and orientation effects with the actual tons per acre of vegetative cover or residue. Values of V' have been computed for various kinds of vegetation or residue and are presented in Figure 73. The basic measurement of tonnage is made by actually weighing samples of the vegetation according to a standard procedure.95 A graphical solution (Figure 74) is used to incorporate V' as the final step in the determination of A', as explained below.

Seasonal Aspects of Wind Erosion

The WEE is based on a monthly period, and K' and modifying factors are not in a form suitable for determining A' season by season, or otherwise. It is emphasized,93 however, that a great variation in wind force occurs through the year. Generally, wind erosion forces are greatest in the spring and least in the summer, but exceptions to this generalization are not uncommon. Reference 93 cites greatest forces in the summer at Laredo, Texas, and Riverside, California, as two examples of exceptional cases.

Tabulations of the best available monthly statistics (Table 31) for numerous stations around the United States are available93 and provide a useful basis for estimating the seasons of maximum and minimum wind activity. These data can be used for judging seasonal aspects and for scheduling landfill operations as explained under DESIGNING FOR WIND EROSION CONTROL.



PROCEDURE:

FOR UNSHELTERED AREA OF APPROXIMATELY EQUAL LENGTH AND WIDTH, FOLLOW THIS EXAMPLE WHERE A'_2 = 86 TONS/ACRE/YEAR, A'_3 = 55 TONS/ACRE/YEAR, AND L' = 600 FT. COPY MOVABLE A'_3, A'_4 SCALE AND PLACE THE COPY ALONG LEFT SIDE OF CHART. MOVE UP TO MATCH 55 (A'_3) ON MOVABLE SCALE TO 86 (A'_2) ON CHART. FOLLOW CURVE FOR 86 TO RIGHT TO INTERSECTION WITH 600 (L'). RETURN HORIZONTALLY LEFT TO MOVABLE SCALE AND READ A'_4 = 42 TONS/ACRE/YEAR. FOR SOLVING THE MORE COMPLICATED CASE WHERE AREA LENGTH GREATLY EXCEEDS WIDTH, CONSULT THE ORIGINAL REFERENCE.[93]

Figure 72. Chart for determining soil loss A'_4 from A'_2, A'_3, and L'.[93]

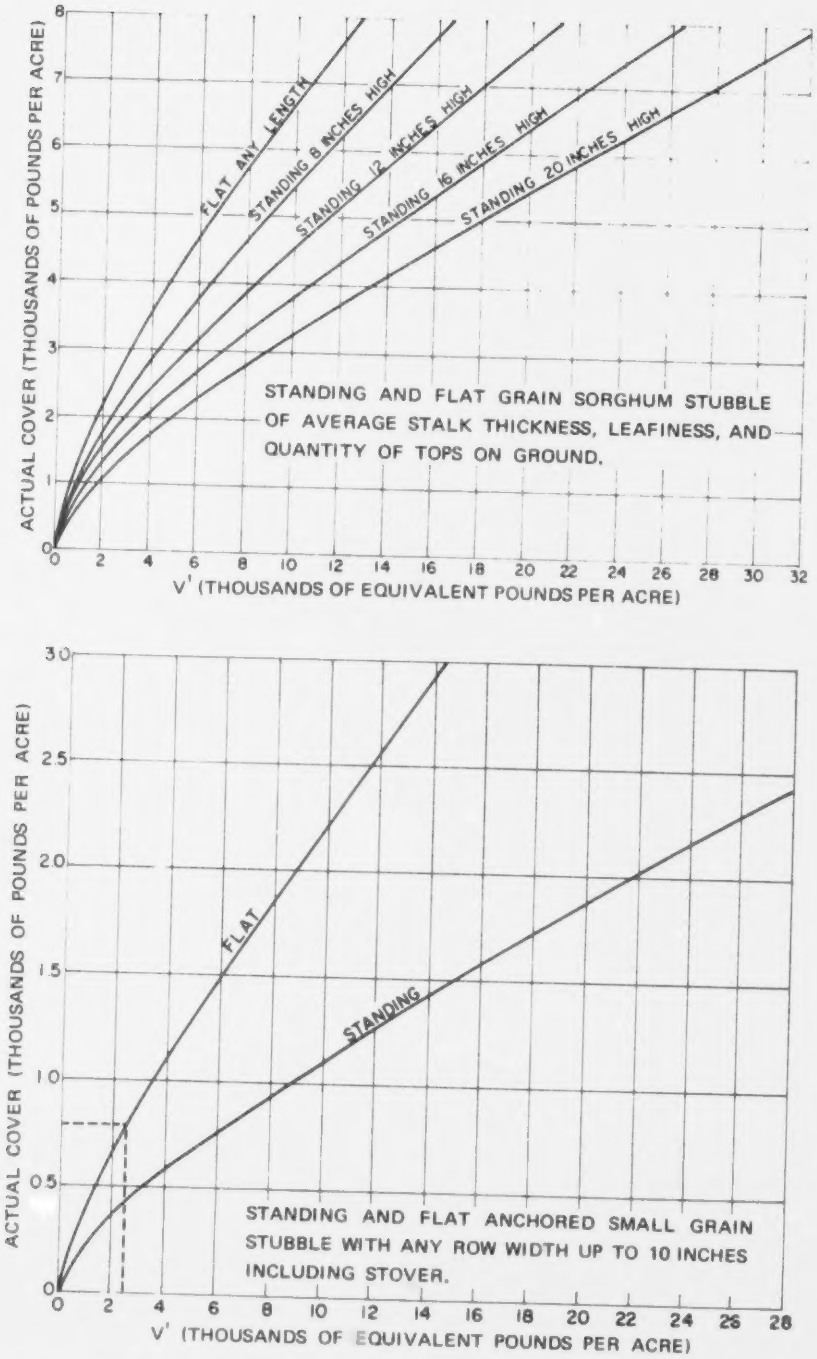


Figure 73. Relationship of factor V' to quantity and type of vegetative cover.[93] For example, 800-lb/acre actual flat residue has equivalent V' = 2500 lb/acre.

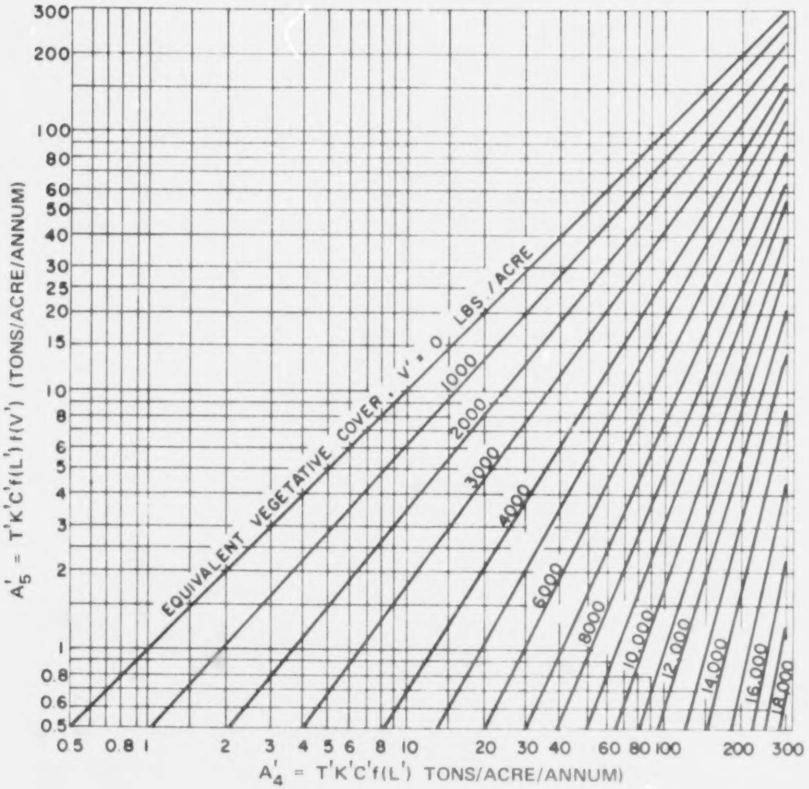


Figure 74. Chart for determining soil loss A'_5.[93]

USE OF WEE FOR DESIGN

The WEE was developed for agricultural use in assessing susceptibility of specific sites to wind erosion and designing control practices to combat erosion. Against landfill erosion, the equation's utility is broadened considerably, since some of the factors that are inflexible in the agricultural situation, and can only be assessed, can be manipulated in the design stage of a landfill.

The five incremental steps in solving Equation 18 are as follows:[95]

Step 1. Determine (Figure 69) an erodibility increment $A'_1 = K'$ that would occur from a wide, isolated, smooth, unsheltered, bare field having a calculated percentage of dry aggregates greater than 0.84 mm in diameter (under climatic conditions as at Garden City, Kansas, where the measurements for the table were made). Adjust K' for knoll configuration where appropriate (Figure 70).

Step 2. Account for the effect of roughness T' (Figure 71), and find the erodibility increment $A'_2 = A'_1 \cdot T'$.

Step 3. Account for the effect of local wind velocity and surface soil moisture C', from Figure 68, and find the erodibility increment $A'_3 = A'_2 \cdot C'$.

Step 4. Account for the effect of length of field L', and determine $A'_4 = A'_3 \cdot f(L')$. Calculation of A'_4 is not a simple multiplication because L', A'_3, and A'_2 are interrelated. A graphical solution of this portion of the equation is given in Figure 72.

Step 5. Account for the effect of vegetative cover in V' (Figure 73), and determine the actual annual erosion for a specific landfill surface $A'_5 = A' = A'_4 \cdot f(V')$. Here again, the relationships among A'_4, A', and V' are not simple. A graphical solution is given in Figure 74.

The WEE is potentially useful for determining acceptability or unacceptability of a landfill design where coupled with a criterion for acceptable levels of annual wind erosion. Ways of reducing high erosion should become apparent when each factor in the equation is carefully considered separately; thus, a manipulation of the orientation of the landfill might reduce L' and, in turn, erosion loss. This and other methods of design modification are discussed below.

DESIGNING FOR WIND EROSION CONTROL

Design for wind erosion control on landfills has considerable flexibility in comparison with control measures available for application to agricultural fields (see EROSION IN THE SOLID WASTE/SOIL SYSTEM). Each factor of the WEE including even C' concerns one or more variables that are at least locally subject to manipulation. The principal techniques for designing new landfills or modifying existing ones are briefly explained below.

Soil Composition

The susceptibility of soils to wind erosion is directly reflected in the K' value, which is a function of the coarse soil fraction. Figure 69 gives the values corresponding to measured percentages of grains over 0.84 mm in diameter. The figure is a basic tool to be used in design for selecting or modifying cover soil type on the basis of sieve analyses of those soils available.

Knoll and Side Slope Configuration

The vulnerability of knoll-like configurations on landfills can be evaluated by the use of Figure 70. An adjustment factor is obtained as an erosion loss percentage of 100 or more in comparison with erosion loss from a similar flat surface. This factor should be used to estimate the effects of sides of landfills that may present a knoll-like configuration toward the prevailing winds. It is apparent from Figure 70 that even gentle windward slopes may cause major erosion concentrations and, therefore, are places in need of stabilization or protection (see Wind Barriers) when exposed to highly erosive winds. It may even be reasonable to arrange side slopes in protected orientation and leeside positions.

Trench Method

Use of the trench method rather than disposing waste in the more common embankment type landfill is highly effective in reducing erosion. Most land burial in the Great Plains has been accomplished by trench method or by filling old excavations.

Length-width and Orientation Configuration

L' is an important variable in the wind erosion process, as indicated previously. On an eroding surface, the rate of soil movement is zero on the windward edge and increases with distance to leeward[95] until, on a large surface, the flow reaches a maximum. At least three approaches are available during the designing of a landfill to reduce L' and soil loss:

a. Orient short dimension parallel to prevailing wind.

b. Use barriers at strategic locations.

c. Use only a small segment of landfill at one time, keeping the remainder protected by vegetation or other means.

Vegetation Cover

The importance of vegetation in reducing wind erosion can hardly be overemphasized. Figure 73 indicates that even the relatively sparse cover provided by crop stubble gives a large equivalent cover for use in the WEE . The effectiveness of vegetation in reducing wind erosion is increased when the growth is erect and tall. Timely seeding and emergence of vegetation are important in reducing bare soil exposure time. However, timing may not be a straightforward matter since coordination with the growing season, windy season, and landfill operations plan must also be assured.

Stabilization with Mulch

The procedure for temporary stabilization of soils with hauled-in vegetative mulches generally consists of: preparing the seedbed, seeding grasses and legumes, choosing and applying a vegetative mulch, and anchoring the mulch.[96]

Wind Barriers

A system of wind barriers may be effective in reducing L' and, in turn, the erosion (according to the WEE). In preparing the barriers, two critical factors are the height that determines sheltered length and the sturdiness to resist overturning. Barriers may consist of slat or brush fences and board walls. For example, slat snow fences cause beneficial eddy effects on the leeward side.

Additives

Since the need for wind erosion protection at landfills is often short-term and may be urgent, emergency methods should be such as can be applied when the need arises and will be instantaneously beneficial. The application of chemicals to stabilize soil cover is one of the most effective quick-response methods (Table 10). The popular procedure of sprinkling with water is temporarily quite effective. Unfortunately, wind erosion is most common in water-deficient areas where, in addition, evaporation rates are usually high.

Special Area

A special area with surface configuration or trench orientation arranged for unusual or severe wind conditions may be reserved. Some areas may experience more than one prevailing wind during a season so that the precautions under Length-width and Orientation Configuration may need to be considered for an oblique, standby area also.

SECTION 12

DUST CONTROL

The generation and dispersion of dust ranks high among problems associated with day-to-day landfilling and waste disposal. Dusty conditions are unsightly and highly irritating to workers. Any dust dispersed beyond the site is bound to cause widespread complaints in the community. Dust from a hazardous waste disposal area carries the added stigma of a health hazard of considerable magnitude. Regardless of whether there is a basis in fact, a nearby neighborhood may suspect that dust coming from an industrial plant waste area contains hazardous waste. This section reviews briefly the techniques for designing against the problem, whether it be a potential health hazard or only a nuisance.

CAUSES AND SOURCES OF DUST

About the only soils that are not capable of producing significant dust are sand or gravel, from which erosional processes of wind and water already have removed the fine material. On just about any construction site, including landfills or hazardous waste disposal areas, some dust inevitably will be generated from the soil on or adjacent to the activity. Cover soil will be the primary source of dust particles, but additional components may be added from the waste material itself, as demolition wastes of plaster, concrete, and wood. Such waste may be dry and partially deteriorated and, therefore, especially susceptible to dust generation.

The causes of dust are usually a combination of the following four separate processes:

a. Breakdown of soil structure.

b. Drying.

c. Vehicle wind eddies.

d. Gusty winds.

Of these factors, gusty winds are not subject to control within economic constraints. Almost as uncontrollable is the creation of vehicle wind eddies; slower vehicle speed might help slightly. The other two aspects, however, are controllable to whatever degree necessitated by the seriousness of the problem and the economics of the landfilling operation. Therefore, the remainder of this section concerns preventing or minimizing a dust problem by taking measures to strengthen the soil structure and to retain soil moisture.

DESIGN FEATURES FOR DUST MINIMIZATION

Several options are available in the design stage for reducing the potential for dust generation. Formulas such as exist for water erosion and wind erosion are not available to quantify or to predict the amount of dust from certain conditions; therefore, design adjustments are somewhat qualitative. Thus, a considerable degree of judgment must be exercised. Also, the trade-off among the various design aspects or cover functions requires that the designer weigh each choice for minimizing dust against the possibly adverse effects to other cover functions.

Haul Roads Limitation

The haul roads for daily operation should be so organized as to concentrate traffic on one or a few routes. This organization reduces to a minimum the length of road or tracks that is subject to producing dust. This procedure follows closely with procedures for maintaining haul roads in a condition for minimization of dust.

Haul Roads Maintenance

One or more of the following maintenance techniques may be appropriate for haul roads:

a. Use clay-poor soils, such as river sand.

b. Surface the road with gravel.

c. Sprinkle with water as needed throughout the day.

d. Spray on or mix in chemical additives.

Selection of Soils

The dust problem can be largely eliminated where it is reasonable to use a granular soil to cover the waste. Soils become progressively less suitable as cover from the point of view of dust in the rank order of increasing clay and silt sizes. The determination of grain size in this case should be based on a standard procedure involving complete breakdown of the soil structure, since this pulverization closely simulates the history of the soil in the field undergoing heavy traffic.

Additives or Waste Oil

To be effective a dust palliative should strengthen bonds between soil particles and hold this strengthened condition for an appreciable period.[97] The additives in Table 10 are grouped according to five general types but are not ranked according to effectiveness; all have shown some promise in laboratory and field testing. Some operators will opt for calcium chloride or waste oil as recommended elsewhere[3] for dust control. Waste oil has some air pollution potential,[98] but when restricted to relatively small landfilling operations, use of waste oil is predominantly beneficial. Otherwise, it seems that some experimentation should be undertaken to develop experience in selecting and using palliatives at landfills. Factors that will have to be considered in making a choice are additive toxicity, duration of effectiveness, cost, stability, and so forth. The designer should not expect or plan to rely on dust palliatives for more than a few months. Beyond this time a vegetative cover should be developed, and the causes of dust may even have been removed from the particular section of the landfill.

Vegetation

The importance and urgency of a vegetative cover for dust control is parallel to the importance of vegetation in controlling wind erosion. Further details are found in Section 11.

SECTION 13

STABILITY OF SIDE SLOPES

Some specific consequences of slope instability can be disruption of transportation, blockage of runoff ditches, or disturbance of building foundations. However, the effect upon an aware and sensitive population can be even more serious, since such an unexpected and unplanned occurrence as a slope failure often implies accompanying pollution of the environment and infers inability of the operator or municipality to handle its engineering problems.

SLOPE STABILITY IN THE SOLID WASTE/SOIL SYSTEM

The special nature of waste-retaining slopes (Figure 75) that makes them somewhat more critical than ordinary fill slopes is the fact that they confine potentially harmful waste. Any failure of the side cover may release contaminants directly into the environment. The specific slope stability and related problems are as follows:

a. Slope failure opening waste cells.

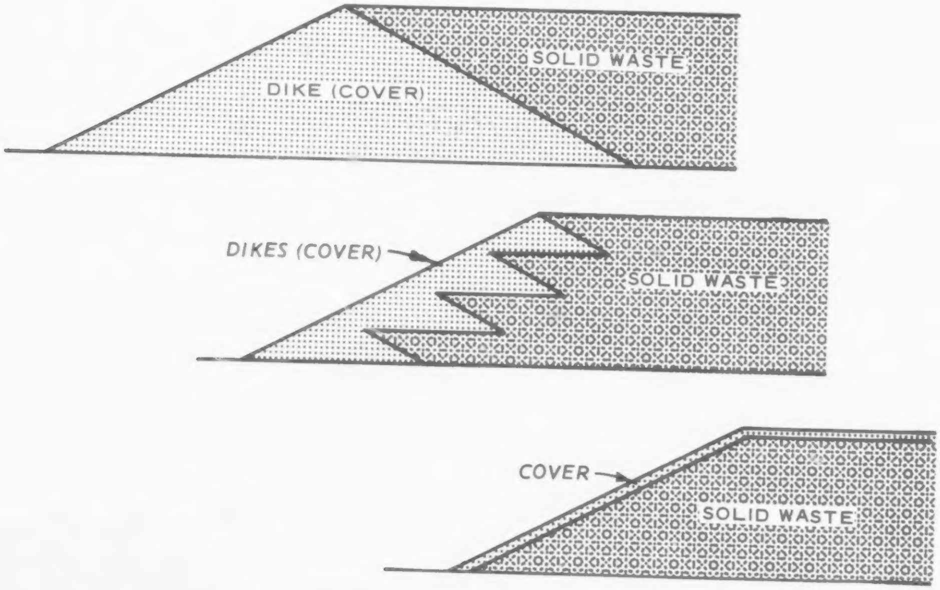


Figure 75. Cover configurations at sloping sides of disposal areas.

b. Slope deformation opening cracks and leading to other problems.

c. Unanticipated lateral seepage of leachate or water.

d. Uncontrolled lateral seepage of leachate or water.

The last two problems are somewhat separate from slope stability yet frequently are involved in a contributory role.

Design for stable slopes usually incorporates features for controlling subsurface drainage and developing adequate shear strength. Features will ordinarily be selected and designed within the constraint of cover material availability. Where inferior soils must be used, it may be necessary to adjust the design accordingly; but adjustments are seldom prohibitively expensive, since slopes are usually not high. Three basic configurations are used for the side or sloping cover at solid waste disposal areas (Figure 75).

EVALUATING STABILITY

The accuracy and results of analyses depend mainly on the accuracy with which shearing strength and slope conditions can be quantified.

Strength of Waste and Soil

Fill slopes in general soil engineering are designed with cognizance of the shear strength of the soil as determined in standard tests. Section 3 reviews tests for soil strength; the same tests apply to soillike wastes. Strength of municipal refuse has not been adequately studied, in part because of the difficulty in obtaining representative samples for testing. Refuse compositions of paper, food, hard plastics, metal, etc., change from day to day, and other changes in properties take place with time due to decomposition and to absorption of water.

A conservative stance can be taken in extreme cases by assuming that the waste itself has no strength and that the strength of the mass behind the side slope is related to the strength of the cover soil in the same ratio as the volume proportion of cover soil (Figure 76). Thus, shearing along any inclined surface involves one or more cover soil layers. For example, if the volume ratio of soil cover to waste is 1:3, the solid waste mass could be considered to have an overall strength of approximately one-fourth that of soil.

Compaction of Soil

Compaction decreases porosity n of a given soil and, in turn, produces a higher ϕ. The following effect has been observed[99] for medium-fine sand:

n , %	ϕ , deg
43.0	32
38.5	34
36.0	37
34.0	40

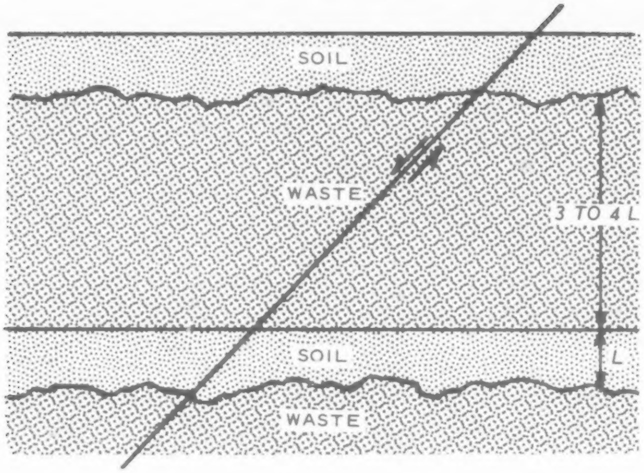


Figure 76. Idealized shear surface cutting landfill mass of waste and cover soil.

Also, see Figure 20 for similar results from a range of granular soils. The effect has been explained[100] to be related to the degree of interlocking of the grains, i.e., the greater the degree of interlocking, the greater the overall shear resistance. Figure 77 illustrates this same phenomenon from a slightly different viewpoint. Specific results are plotted for triaxial compression tests on another medium-fine sand compacted to two different density conditions (in terms of initial void ratio e_o). The material compacted to low e_o had extra strength manifested as a peak on the plot. Beyond this peak, the stress dropped away to a value consistent with the loosely packed specimen as expansion destroyed the interlock.

Foundation

Most of the failures that occur in soil embankments originate in weak foundation soils. Accordingly, it is essential that strength and consolidation characteristics be evaluated even though the foundation is not part of the cover per se. A preliminary evaluation should be made routinely. Where there is evidence that the foundation is weaker than the soil to be used as cover, it is prudent to undertake a stability analysis, if necessary, with assistance from an experienced agency. It will be shown in STABILITY ANALYSIS how methods of analysis are organized to include the foundation in the search for the potential failure surface.

Groundwater

Groundwater can have an important effect on the stability of a slope. Where the phreatic surface lies below the mass of potential instability, the effect is insignificant or possibly even beneficial by virtue of capillarity. The importance of groundwater increases with depth below the phreatic surface

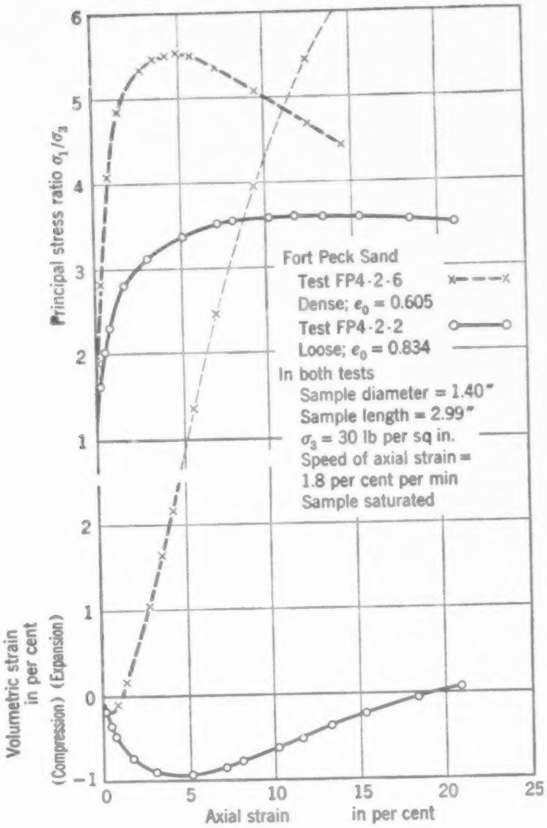


Figure 77. Behavior of loose and dense specimen of medium-fine sand during triaxial compression.[101] (Reproduced by permission of John Wiley and Sons.)

because of increasing pore pressure and corresponding reduction in S (Equation 5).

Three cases of various degrees of importance of groundwater are idealized in Figure 78. The preferred condition in the present state of the art of landfill operation and maintenance is Case I where the phreatic surface is located below the original ground surface and below the landfill waste cells and side slope. Here, the cover soil excludes so much rainwater as to prevent a rise of the level of saturation into the landfill. The effect of the groundwater on the side slope is negligible and can be ignored.

Case II in Figure 78 represents the extreme where the waste and part of the impounding slope or dike are saturated. Actual instances of Case II are abundant in the mining industry where plant tailings are dumped and remain in a saturated condition. Industrial sludges and slurries are similarly impounded in a saturated condition. Water soon seeps to an equilibrium (steady) seepage configuration so that a flow net[101] can be used to estimate pore pressures for the stability analysis.

Case III is an intermediate condition between Cases I and II. Water percolating through the cover establishes a phreatic surface that may fluctuate within the solid waste mass according to climatic conditions, particularly

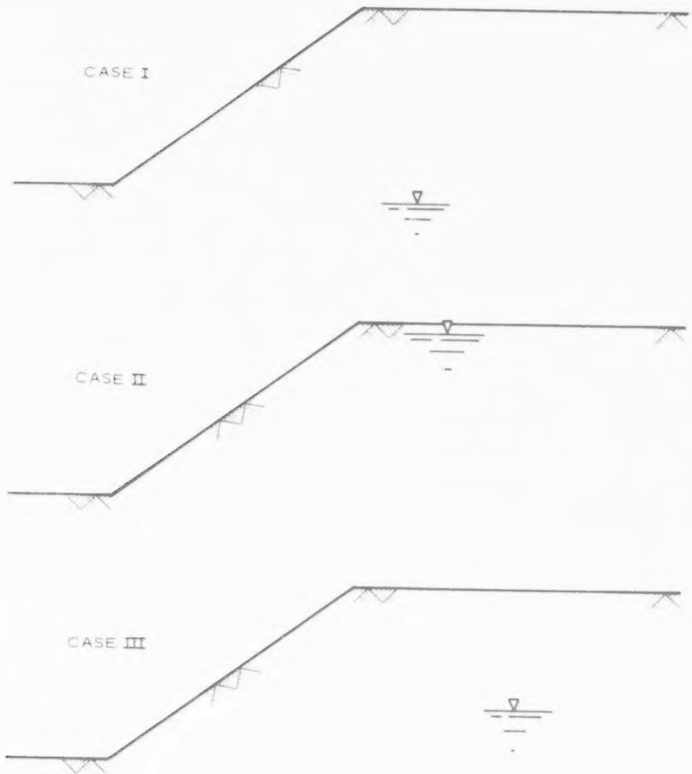


Figure 78. Three cases of groundwater conditions in a landfill.

in humid regions. Conditions expected to occur over the design life of the fill must be predicted and used to estimate the extreme phreatic surface position. For sustained high water levels, Case III might approach Case II as far as transient pore pressure effects on stability. A temporary rise might only impose a weight surcharge if short in duration.

Changing Conditions

Changes of conditions that influence slope stability mostly involve the groundwater regime. Freeze/thaw change is usually seasonal, whereas dry/soak change is seasonal or in association with short, drastic climate episodes. The third change, a rise of the groundwater table into the solid waste cell, marks flow to a new water table equilibrium after disturbance of the old one by deposition of the solid waste.

In effect, the freeze/thaw and dry/soak phenomena impose temporary perched-water conditions on the cover soil. Soils frozen early in the season thaw in the spring from the top down. Thaw water may be trapped over frozen soil to form a shallow, saturated zone (Figure 79) that is susceptible to sliding (see Section 16). Similarly, experience indicates that shallow sliding sometimes occurs in clay embankments after heavy rainfall.[102] This

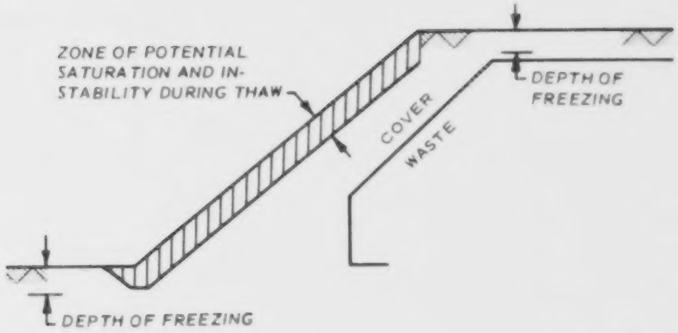


Figure 79. Need for thick soil cover in thawing landfill slopes.

instability presumably results from rapid saturation of a shallow zone previously made permeable, porous, and weak by formation of drying cracks.

STABILITY ANALYSIS

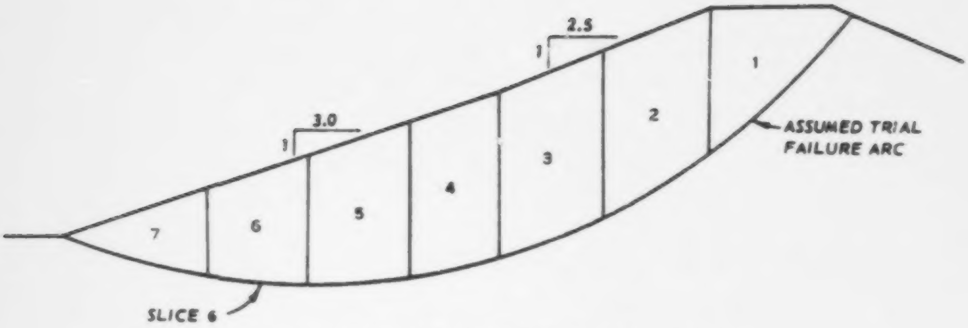
Engineering analyses of slope stability are based on the concept that a slope fails, unless the resultant resistance to shear on every surface traversing the fill is greater than the resultant of all shearing forces exerted on that surface by the mass above. The surface that is most likely to fail is called the critical surface. The factor of safety (FS) quantifies the ratio of resisting forces to driving forces.

Analytical Procedures

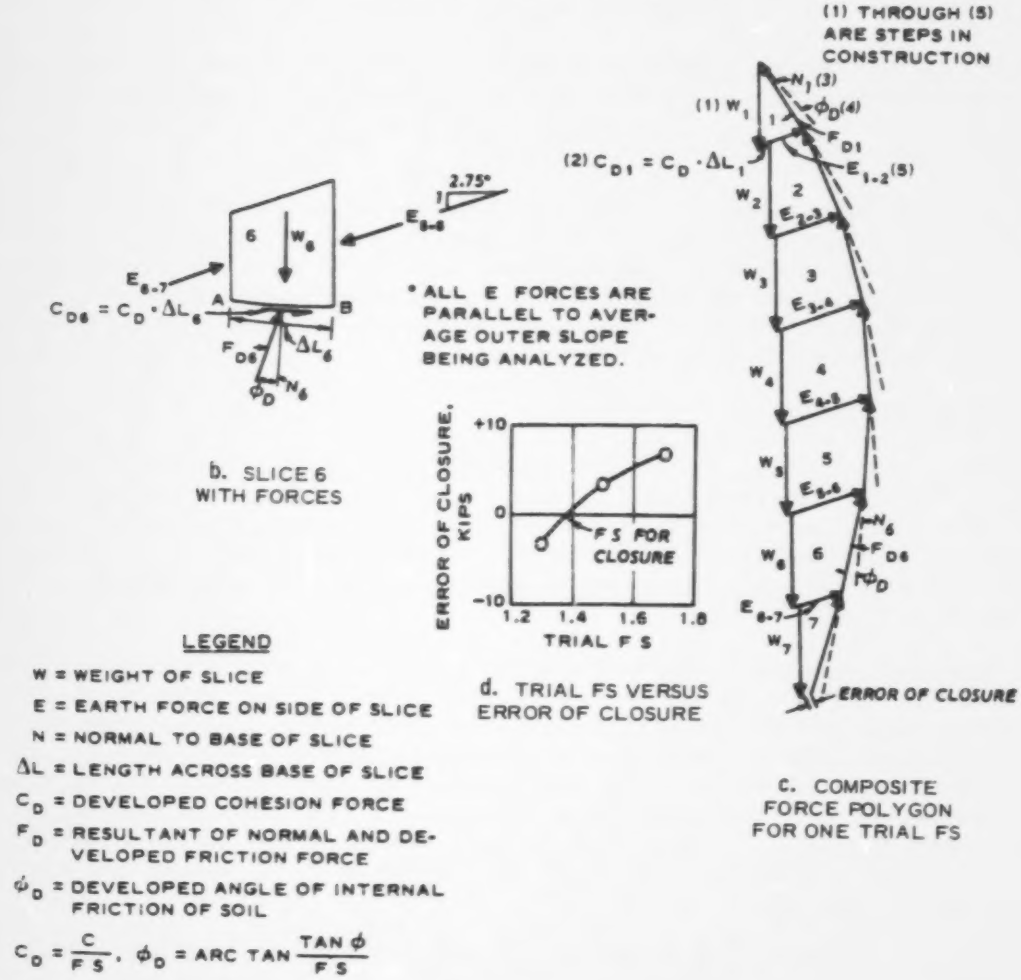
Determination of the location of the critical surface usually requires successive trial analyses of likely candidates. Each trial evaluates a surface having the shape of a circular arc within the foundation and/or the embankment or a composite of a long horizontal plane in a foundation stratum connecting with diagonal planes up through the foundation and embankment to the ground surface.[102]

Analyses assuming a circular arc failure surface are made using either the modified Swedish method[14] that considers forces on the sides of slices within the mass, or the simpler Swedish method of slices that assumes that side forces are equal in magnitude and parallel to the base of each slice. The wedge method for planar sliding surfaces[14] is appropriate for weak foundations requiring flat slopes or for an otherwise strong foundation containing a thin weak stratum. Computer programs are available for the trial analyses; a vector solution of the modified Swedish method is given here to illustrate the general concept.

The sliding mass is divided into a number of slices of convenient width as shown in Figure 80. Where the failure arc passes through more than one type of soil, applicable values of shear strength are used for each slice. Slice 6 with forces acting on it is shown in detail below as an example. The force W_6 is the total weight of the slice. The resisting cohesive force C_{D6} is assumed to act parallel to chord AB and is equal to chord AB times


2.5
1
1
3.0
1
1
2
3
4
5
6
7
ASSUMED TRIAL FAILURE ARC
SLICE 6

a. EXAMPLE EMBANKMENT SECTION


(1) THROUGH (5) ARE STEPS IN CONSTRUCTION
N_1 (3)
(1) W_1
ϕ_D (4)
F_{D1}
(2) $C_{D1} = C_D \cdot \Delta L_1$
E_{1-2} (5)
W_2
E_{2-3}
W_3
E_{3-4}
W_4
E_{4-5}
W_5
E_{5-6}
N_6
W_6
F_{D6}
ϕ_D
E_{6-7}
W_7
ERROR OF CLOSURE
2.75*
1
6
W_6
E_{5-6}
E_{6-7}
$C_{D6} = C_D \cdot \Delta L_6$
A
B
F_{D6}
ΔL_6
ϕ_D
N_6
* ALL E FORCES ARE PARALLEL TO AVERAGE OUTER SLOPE BEING ANALYZED.
+10
0
−10
1.2
1.4
1.6
1.8
ERROR OF CLOSURE, KIPS
TRIAL F S
F S FOR CLOSURE

b. SLICE 6 WITH FORCES

d. TRIAL FS VERSUS ERROR OF CLOSURE

c. COMPOSITE FORCE POLYGON FOR ONE TRIAL FS

LEGEND

W = WEIGHT OF SLICE

E = EARTH FORCE ON SIDE OF SLICE

N = NORMAL TO BASE OF SLICE

ΔL = LENGTH ACROSS BASE OF SLICE

C_D = DEVELOPED COHESION FORCE

F_D = RESULTANT OF NORMAL AND DEVELOPED FRICTION FORCE

ϕ_D = DEVELOPED ANGLE OF INTERNAL FRICTION OF SOIL

$C_D = \frac{C}{F\,S}$, $\phi_D = \text{ARC TAN}\,\frac{\text{TAN}\,\phi}{F\,S}$

Figure 80. Modified Swedish method of finite slice procedure with no water forces.[14]

the developed unit cohesion C_D . The force F_{D6} acting at an angle ϕ_D with N6 the normal to AB is the resultant of the normal force at the base and the developed frictional force.

Assuming a trial FS, the forces acting on each slice are combined into the composite force polygon (Figure 80). Use a convenient force scale and follow steps 1 through 5 on each slice in sequence; start at the uppermost (Slice 1).

Step 1. Draw the W vector.

Step 2. Draw the C_D vector parallel to the base of the slice.

Step 3. Draw a line normal to the base of the slice from the upper end of the W vector.

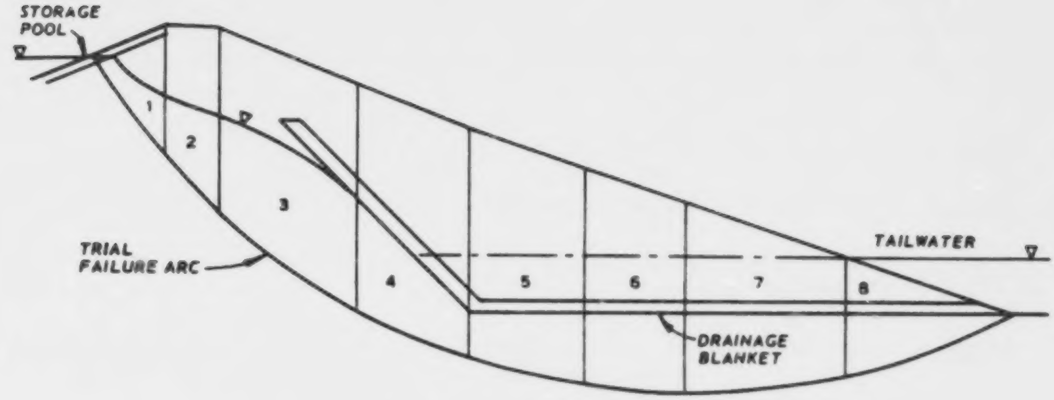
Step 4. Construct a line at ϕ_D from the normal line to establish the direction of vector resultant of the normal and frictional forces on the base of the slice (e.g., F_{D1}).

Step 5. From the head of the C_D vector, draw the side earth force vector E parallel to the average embankment slope to intersect the resultant vector, thereby closing the force polygon. This establishes the magnitude of the resultant vector (F_{D1}) . The forces on each subsequent slice are then constructed using the E vector of the previous slice as a base. The composite force polygons must be drawn to a large scale to ensure accurate results, since they are cumulative-type diagrams in which small errors can have a large effect on the error of closure. To obtain the FS of balanced external forces, composite force polygons for different trial FS are constructed to determine which one results in closure. The errors of closure for each trial composite force polygon are plotted versus the trial FS as shown in Figure 80. A smooth curve drawn through the plotted points establishes the FS corresponding to zero error of closure.

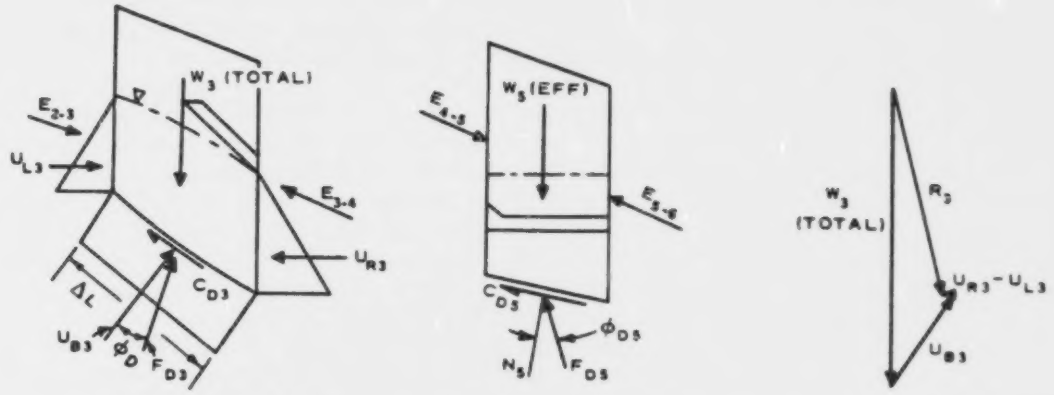
Steady Seepage Analysis

Seepage through the side slope tends to reduce stability by increasing the driving forces and decreasing the resisting forces due to uplift (Equation 5). In the case of steady seepage, the water force acting on each slice is determined from flow nets or assumed to vary linearly below the saturation line. The forces on typical slices are shown in Figure 81. To simplify construction of the composite force polygon, the resultant of the weight and water forces for each slice having a sloping water surface is determined (Figure 81). The procedure for determining the FS for zero error of closure is the same as that shown in Figure 80.

Analysis for steady seepage Cases II and III (Figure 78) may warrant the use of composite strength envelopes (Figure 82). The applicable shear strength depends on the developed normal force, which is influenced by the side earth forces. Consequently, the applicable shear strength should be


STORAGE POOL
1
2
3
4
5
6
7
8
TRIAL FAILURE ARC
TAILWATER
DRAINAGE BLANKET

a. EMBANKMENT SECTION


W_3 (TOTAL)
E_{2-3}
U_{L3}
E_{3-4}
U_{R3}
C_{D3}
ΔL
U_{B3}
ϕ_D
F_{D3}
W_5 (EFF)
E_{4-5}
E_{5-6}
C_{D5}
ϕ_{D5}
N_5
F_{D5}
W_3 (TOTAL)
R_3
$U_{R3}-U_{L3}$
U_{B3}

b. SLICE WITH SLOPING WATER SURFACE

c. SLICE WITH HORIZONTAL WATER SURFACE

d. RESULTANT OF WEIGHT AND WATER FORCES

U_R = WATER FORCE ON RIGHT SIDE OF SLICE
U_L = WATER FORCE ON LEFT SIDE OF SLICE
U_B = WATER FORCE ON BASE OF SLICE

Figure 81. Forces acting on typical slices.[14]

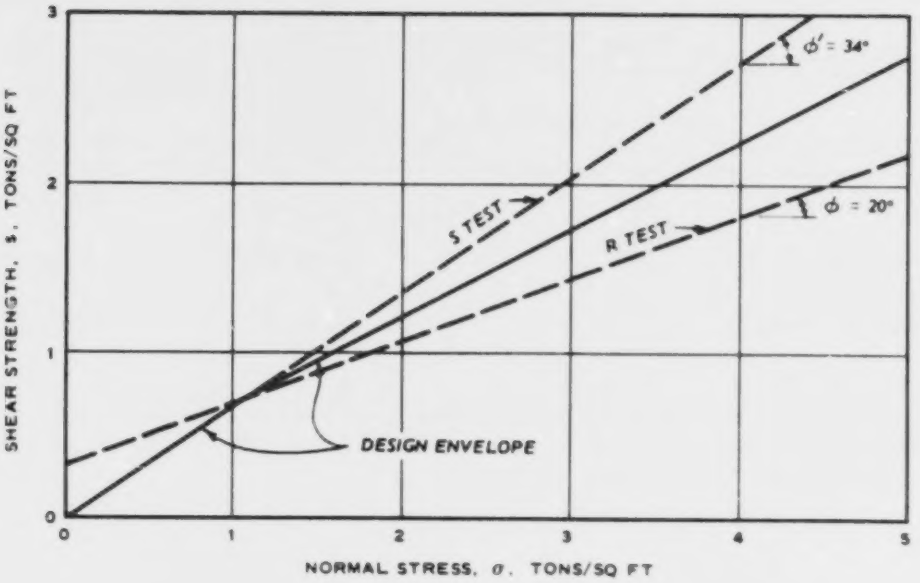


Figure 82. Example design envelope for Cases II and III.[14]

checked by trial and error as the composite force polygon is constructed. The S strength is assumed as a basis for ϕ_D in the first portion of the composite force polygon, and the resulting developed normal force divided by ΔL is compared with normal stress at the intercept of the S and R envelopes to determine when the $(R + S)/2$ strength or the S strength governs (Figure 82).

Expedient Methods

Infinite slope. A special, simple analysis is available for cohesionless soil embankments. The infinite slope procedure[14] represents rather shallow sliding and seems particularly appropriate for relatively thin cover over sloping waste, where shallow sliding can be serious. For dry conditions, the safety factor reduces to

$$FS = \frac{\tan \phi}{\tan \beta} \qquad (19)$$

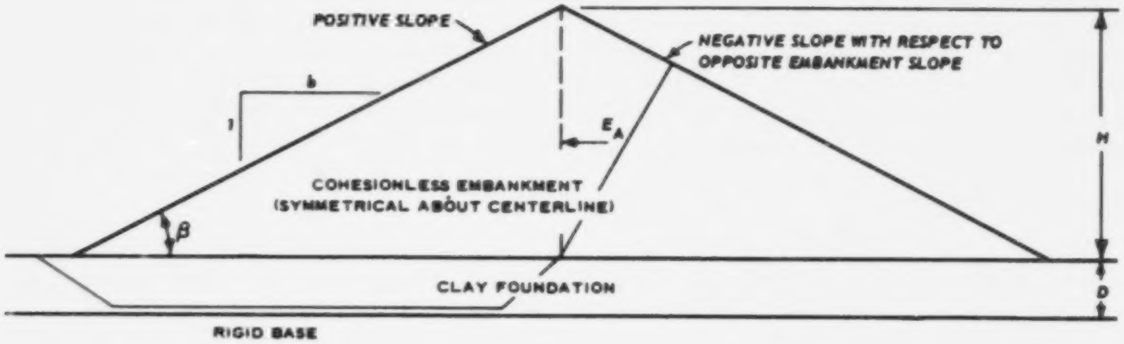
where β is slope inclination. The equivalence of the friction angle and inclination at the threshold of failure is reflected in the general correspondence of the observed angle of repose and measured friction angle in cohesionless soils (Table 32).

Design charts. Numerous design charts have been prepared for rapidly designing slope inclination on the basis of soil c and ϕ.[14,103] One chart procedure is reviewed here as an example intended for embankments of cohesionless soil resting on shallow clay foundations (Figure 83). The method (Figure 84) utilizes an active earth pressure coefficient K_A corresponding to

TABLE 32. ESTIMATES OF REPOSE AND FRICTION ANGLES OF COHESIONLESS SOILS

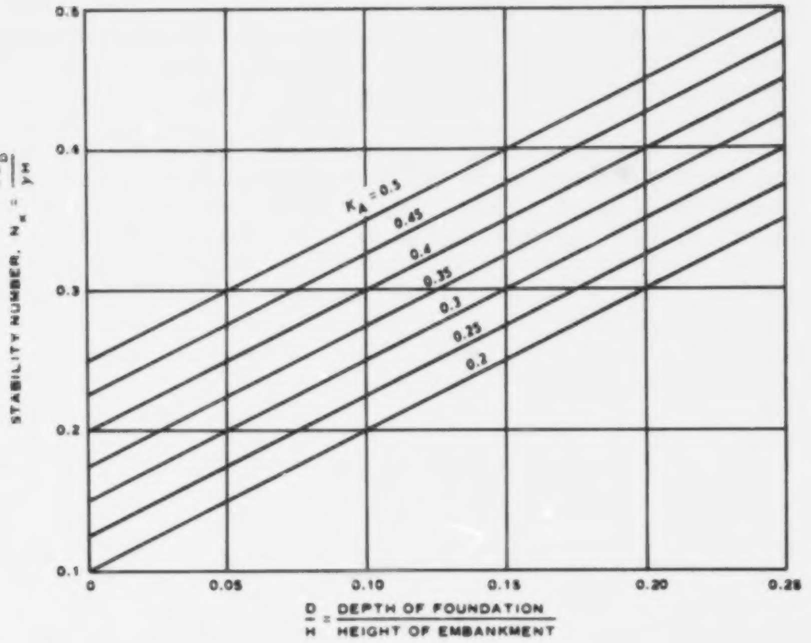
Soil Description	Angle of Repose * deg	Friction Angles, deg At Ultimate Strength	Friction Angles, deg At Peak Strength
Silt	26 - 30	26 - 30	28 - 34
Uniform sand	26 - 30	26 - 30	30 - 36
Well-graded sand	30 - 34	30 - 34	34 - 46
Sand and gravel	32 - 36	32 - 36	36 - 48

* Lower values generally for soft or well-rounded particles, at dense packing, or at high normal stresses.

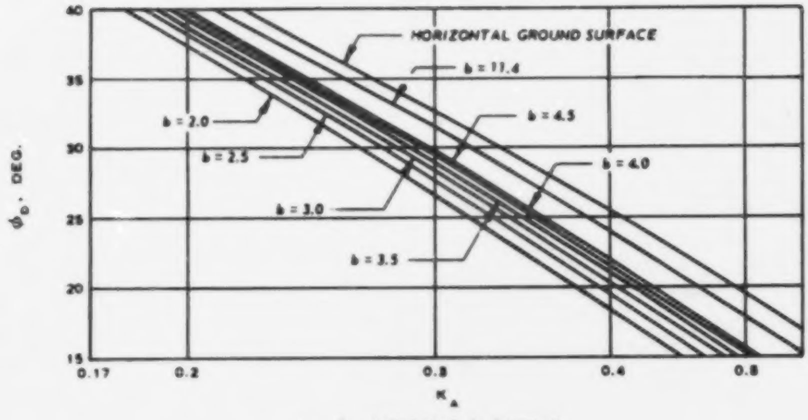

POSITIVE SLOPE
b
1
NEGATIVE SLOPE WITH RESPECT TO OPPOSITE EMBANKMENT SLOPE
E_A
H
COHESIONLESS EMBANKMENT (SYMMETRICAL ABOUT CENTERLINE)
β
CLAY FOUNDATION
D
RIGID BASE

H = HEIGHT OF EMBANKMENT
D = THICKNESS OF CLAY FOUNDATION LAYER
K_A = RATIO OF HORIZONTAL TO VERTICAL EARTH PRESSURES, ACTIVE CASE
b = COTANGENT OF SLOPE ANGLE β
γ = WEIGHT OF EMBANKMENT AND FOUNDATION MATERIAL PER UNIT OF VOLUME
c = COHESION PER UNIT AREA OF FOUNDATION SOIL

Figure 83. Cross section and symbols for stability chart.[14]



a. N_K VERSUS K_A AND $\frac{D}{H}$



b. ϕ_D VERSUS b AND K_A

Figure 84. Stability chart for cohesionless embankment on plastic foundation.[14]

the ratio of the horizontal to vertical earth pressures at the center of the embankment.[14] Chart 2 in Figure 84 gives values of K_A for a horizontal ground surface and for negative slopes (i.e., reverse slope on opposite side of embankment). First try a value of K_A for an assumed embankment slope to obtain a value of the stability number N_K and a corresponding slope. This slope can then be used to determine a second trial value of K_A , if necessary, a revised stability number and slope, and so forth.

Consider as an example a homogeneous retaining dike 40 ft high, having a shear strength corresponding to ϕ of 28 deg and a unit weight of 120 lb/ft^3 to be constructed on a layer of clay, 4 ft thick, having a Q-test shear strength of 1200 lb/ft^2. Use a FS of 1.3. The developed angle of internal friction ϕ_D of the dike soil is 22 deg ($\tan \phi_D = 0.532/1.3 = 0.409$). The developed cohesion C_D of the foundation soil is $1200/1.3 = 923$ lb/ft^2. The ratio of D/H is 4 to 40 or 0.1. The first trial value of K_A from Chart 2 (Figure 84) is 0.35, assuming a slope b of 1V on 2H. For $D/H = 0.1$ and $K_A = 0.35$, the stability number N_K is 0.285 in Chart 1. Solving for b ,

$$b = \frac{N_K \gamma H}{C_D} = \frac{0.285 \times 120 \times 40}{923} = 1.482$$

Additional trials of K_A appear unnecessary, and this foundation should remain stable at a higher inclination than allowed by Equation 19 of the infinite slope analysis.

DESIGNING FOR SLOPE STABILITY

Foundation Evaluation

Examine foundation conditions, sampling and testing if necessary, to assure that the foundation is not weak and likely to participate in displacement of embankment or cover above. S tests characterize long-term strength and stability.

Stability Analysis

A stability analysis should be required for Case II in Figure 78, for weak foundations, and for slopes exceeding a certain height found to be limiting by experience. Other bases for requiring analysis are implicit, serious consequences of slope failure by virtue of toxicity or fluidity of solid waste.

Soil Selection

Selection of soil for embankments should be influenced by estimates or tests for shear strength of available soils. Allowance should be made for the compaction and corresponding strengthening effect (see Compaction of Soil). The most appropriate test is usually the S test in which drainage is permitted and pore pressure not allowed to develop. The Q strength is applicable to end of construction loading while the S strength is applicable to long-term loading conditions.

Slope Inclination

Decreasing the design inclination is directly effective in increasing stability of soil slopes. In fact, a simple rule of thumb of not exceeding 1V on 4H (or other inclination shown by experience or analysis to be relatively stable) would assure satisfactory slope performance in most cases.

Seepage Control

The subsurface conditions with respect to saturation and location of the phreatic surface should be established during the design stage. If an unsaturated condition cannot be assured by design or cannot be confidently predicted otherwise, it may be necessary to assure conservatism in designing for strength, i.e., by assuming a particularly weak material. In so doing, it will be possible to accommodate transient saturation conditions. Several design features for keeping the phreatic surface below a certain level within the slope or dike retaining structure are described below. Remember that seepage usually releases leachate; therefore, a plan for collection, storage, treatment, and disposal may be needed.

Underdrains. The purpose of an underdrain or drainage blanket (Figure 85) is to keep the top flow or phreatic surface well within the dike where pore pressure can cause no undesirable action (see Toe drains). Thickness of the blanket should be at least 18 in.[102] Poorly graded sand and gravel are recommended as under LAYERING in Section 5. The possibility of clogging by biological or slime buildup should be considered.

Toe drains. A toe drain is a prism of relatively coarse material, such as sand or gravel, placed at the base of the slope. This coarse prism tends to concentrate seepage passing through the slope along the toe and thereby prevents formation of a wet slope. A toe drain also adds strength to dike or landfill cover, since the coarse material, when compacted, tends to have a higher friction angle than the finer soil above. A toe drain should be designed on the basis of a realistic seepage flow pattern, but it can be estimated roughly in proportions as shown in Figure 85.

Cutoffs. Cutoffs are impervious walls incorporated below the side slope or dike to block seepage through foundation soils. Cutoffs are not a part of the cover, but they are related in function. A cutoff reduces seepage to levels where no significant effect on slope stability can develop.

Allowance for Freeze/Thaw and Dry/Soak

A design for stability of slopes that are susceptible to freeze/thaw or dry/soak activity provides sufficient side slope soil thickness. Thus, in Figure 79, the soil may thaw to a mushy consistency of little or no strength to an appreciable depth, yet the slope will remain stable by virtue of the strength of soil remaining below for any conceivable, critical shear surface.

Special Compaction

Specifications can be particularly stringent on compaction to be obtained

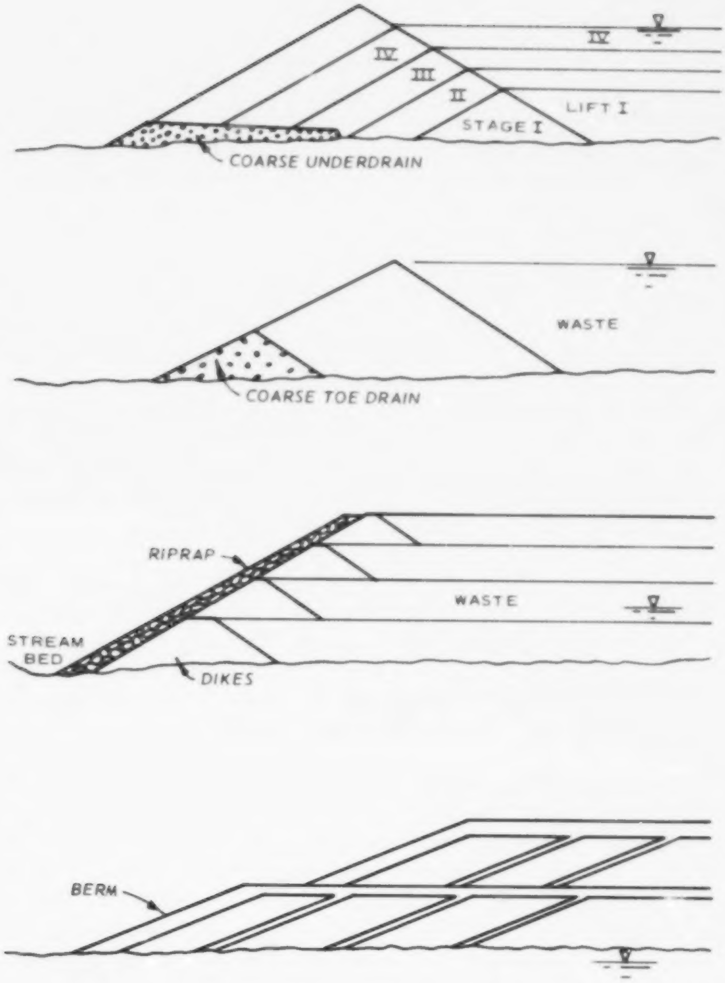


Figure 85. Construction of solid waste retaining dikes and slopes.

in retaining slope cover, since these soils are not based on spongy waste. These specifications should require that the soil be compacted with reference to standard testing procedures. Such requirements usually necessitate field tests for quality control or quality assurance. Alternately, a certain system of compaction field equipment can be specified on the basis of approximate correlation of certain compactive effort with this equipment to desired in-place density (see COVER COMPACTION in Section 5). Lift thickness should also be prescribed and, as a first approximation, might be 1 ft for soils.

Zone Construction

Zone construction refers to the rather sophisticated procedure of dike or dam construction where separate materials are used in zones for strength or seepage effects. The simplest zoning involves the incorporation of an impervious wall along the waste side or within a cover or dike to impede the flow of water. Zone construction might also be undertaken where insufficient amounts of a single type of soil are available.

Toe Protection

Cover slopes extending into a surface drainage channel might, under flooding conditions, be severely eroded, oversteepened, and weakened to the point of failure. Where such a vulnerability is indicated by preliminary study, riprap or other slope protection should be incorporated in the design to absorb the energy of the flowing water. Incorporating berms might also be considered.

Berms

Another design for increasing stability uses a berm or system of berms (Figure 85) rather than having a single unbroken inclination. Berms reduce the overall inclination and thereby lower the driving force in the stability analysis; berms also reduce slope erosion. Level-by-level construction provides ready-made berms, and the berms may actually facilitate the operation by providing working space for construction of the final side slope cover on the lift above.

Reinforcement

Consider incorporating brush and similar wastes in the form of thin horizontal mats at intervals in the waste slope where problems are anticipated. As these mats are exposed by erosion, they help slow the water and reduce its eroding potential.[72] Flat mats of scrap tire sidewalls have been suggested[104] to strengthen embankments and simultaneously to use another troublesome solid waste. With sufficient strengthening, a landfill side slope inclination and height can be increased to achieve more efficient use of the site.

Trench Burial

The trench method of waste disposal circumvents slope stability problems, since the trench provides containment on all sides of the waste material. The effectiveness of the trench method is highly dependent, however, on the nature of soil, rock, or liner material below; other criteria for choosing this method of disposal are beyond the scope of this manual.

SECTION 14

TRAFFICABILITY

Trafficability of landfill cover is defined as the capacity of the soil or other material to support vehicle traffic. Factors influencing trafficability of cover soils include not only the many variables that combine to determine the strength but also the slope, condition of underlying solid waste, and geometrical obstacles, such as drainage ditches.

TRAFFICABILITY ON THE SOLID WASTE/SOIL SYSTEM

Trafficability problems generally involve bearing capacity, traction capacity, slipperiness, or stickiness. Bearing and traction capacities[6] are primarily functions of soil strength (or shearing resistance). Trafficability bearing capacity concerns the ability to support a vehicle without undue sinkage; traction capacity concerns the ability to develop sufficient resistance between the vehicle wheels or tracks and the soil for the necessary forward thrust. Trafficability of a soil is considered adequate for a given vehicle if the soil has sufficient bearing capacity to support the vehicle and sufficient traction capacity to enable the vehicle to develop the forward thrust necessary to overcome its rolling resistance. Obviously, the poorer bearing capacity of underlying solid waste can dominate trafficability on some landfills.

The two other characteristics, slipperiness and stickiness, also affect the operation of a vehicle. Slipperiness is a deficiency of traction capacity in a thin, surficial layer of a soil, which is otherwise trafficable. A vehicle immobilized solely because of slipperiness spins its wheels or tracks and no longer moves forward, yet does not sink excessively. Stickiness is the characteristic of a soil to cling and accumulate on the running gear of vehicles. Rolling resistance of the vehicle is then increased, and steering becomes difficult. In extreme cases, stickiness can "freeze" the running gear of a vehicle. Finally, there is the problem of tracking sticky mud from a landfill to the adjacent public roads.

The concept of trafficability[6] used in this manual has been developed primarily for military purposes and has required two modifications for adaptation to use in solid waste coverage. First, cover soil is always placed in a remolded condition, and generalizations from published soil test data must be used selectively to avoid undisturbed, original strength characterization. This restriction does not appear serious, since undisturbed soil strength is essentially canceled out of the soil rating discussed below. The second modification is that most existing vehicle ratings are for military vehicles, and some judgment and selectivity are necessary in applying established vehicle ratings to landfill equipment. Construction-type vehicles are emphasized for their similarity to those used in landfill operations.

EVALUATING SOIL TRAFFICABILITY

It has been demonstrated that the performance of vehicles in terms of "go"* and "no go," slope-climbing ability, drawbar pull, and force required to tow can be predicted with reasonable accuracy for given soils in the absence of a thin, soft surface layer. The basic indices are the cone index (CI) and the remolding index (RI) as explained under STRENGTH TESTS in Section 3.

Rating Cone Index

The rating cone index, defined

$$RCI = CI \times RI$$

expresses the probable strength of the specific soil under repeated traffic. In the relationships for RI and RCI, the CI for more or less undisturbed soil cancels, and the RCI largely represents the trafficability strength of remolded soil. Accordingly, the RCI is directly applicable to solid waste cover where the soil is always in a remolded condition.

Vehicle Cone Index

The minimum RCI, just sufficient for 50 passes of a specific vehicle, is called the vehicle cone index (VCI). If the RCI is higher than the VCI of a particular vehicle, at least 50 successful passes can be expected along the same straight path, or one such vehicle can be expected to execute severe maneuvers without becoming immobilized. Correlations of VCI with RCI are most consistent for a critical layer, which is 6-12 in. deep in a normal soil profile, i.e., where CI increases or remains constant with depth. The trafficability classification scheme described herein is based on soils data (e.g., see Figure 86) from this 6- to 12-in. layer.

Fine-grained Soils

In general, the soil layer between 6- and 12-in. depths is most critical for fine-grained soils and sand with fines (poorly drained). However, the critical depth can vary with the strength profile of the soil and the vehicle type and weight.[105] The "go" ability of a given vehicle in fine-grained soils is assured if the RCI in the critical layer is equal to or greater than the VCI assigned to that vehicle. In general, an RCI equal to 50 percent of VCI indicates sufficient strength to permit one or two straight passes.[106] If RCI is greater than VCI, additional traction is available to

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* In trafficability,[6] "go" means 50 passes of a given type vehicle along a line or severe maneuvers by one vehicle without immobilization.

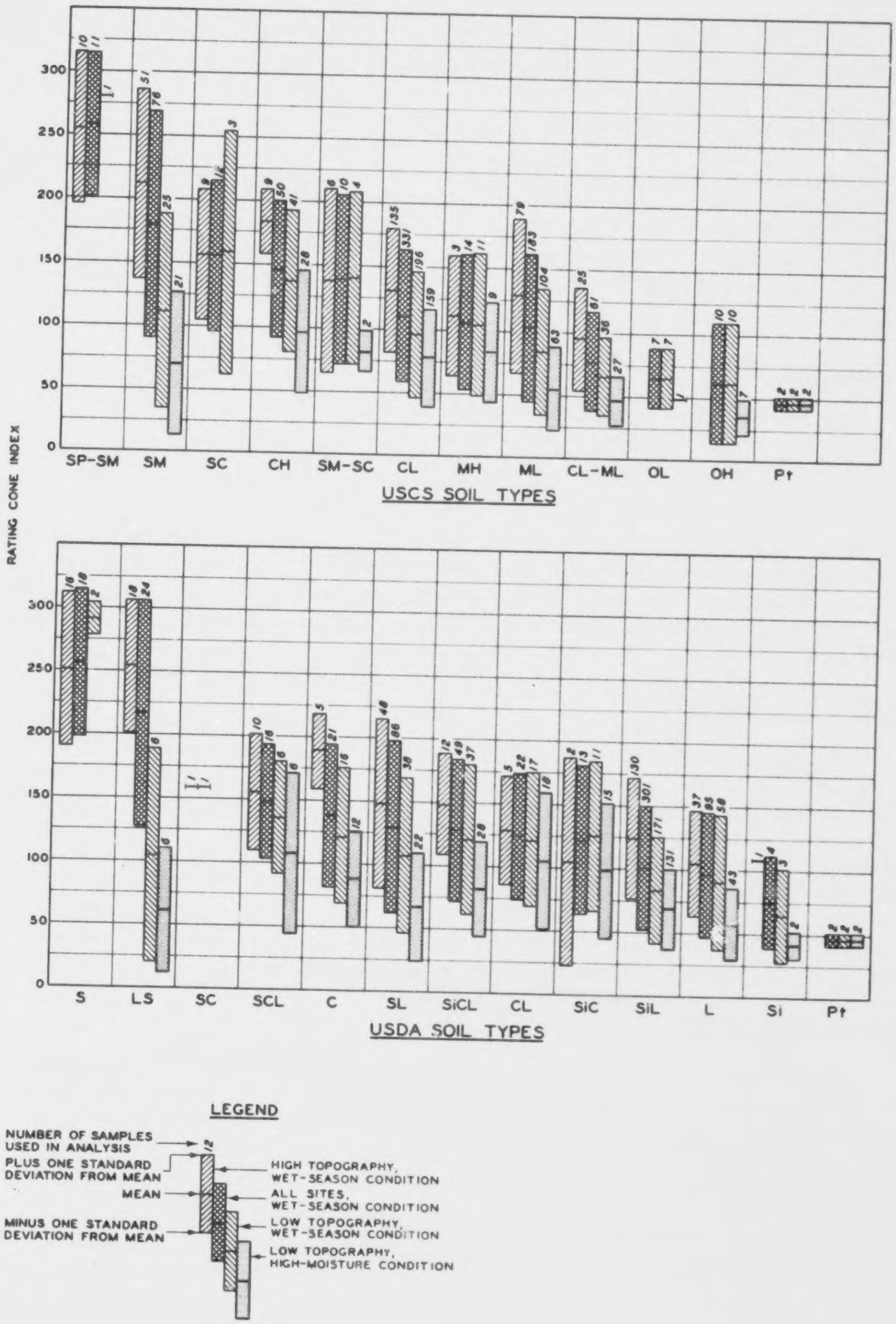


Figure 86. RCI means and ranges for various soil types.[6]

accelerate, negotiate slopes, or tow extra load. VCI's for numerous military vehicles are available[107] along with relationships for computing mobility indexes and relating these indexes to drawbar pull, slope, and required towing force.

Coarse-grained Soils

For coarse-grained soils or clean sands, CI measurements alone are adequate to quantify trafficability. Usually, the strength is not altered significantly by changes in water content. Clean sands possess adequate strength to support many types of vehicles without excessive sinkage. In clean sands, the first pass is the most critical, and subsequent passes are usually made with less difficulty. The 0- to 6-in. depth is considered the critical layer for coarse soils.

Tracked vehicles experience little or no difficulty traversing level, clean sand. The effect of soil strength on performance of a given tracked vehicle is small; however, a significant difference in performance exists among vehicles having other types of track systems. A wide range in wheeled-vehicle performance occurs as a result of changes in tire pressure, number of tires, and tire size.

Soil Moisture Categories

A principal factor influencing the trafficability of a soil is its water content. Accordingly, consideration must be given to conditions of cover soil drainage and climate, both of which affect trafficability through their effect on soil moisture. Two topography-drainage site classes and three moisture-season site classes are distinguished separately or in combinations (Figure 87).

a. Low topography. Low topography is defined[6] as that at which a water table exists within 4 ft of the surface, permanently or intermittently during the year. Such sites usually occur as bottomlands, lower terraces, or occasionally as upland flats associated with impervious pans. They are generally characterized by poor to fair external drainage and moderately poor to very poor internal drainage.

b. High topography. Sites of high topography have water tables at depths greater than 4 ft at all times. These sites are characterized by pervious soils and moderate to good internal and external drainage. They are usually located on ridges or upper slopes.

c. Wet-season condition. The wet-season condition is intended to represent the average moisture condition prevailing in soils during the wet season. Exclusion of some of the drier sites from the data base used in trafficability studies tended to bias averages toward wetter-than-average conditions.

d. High-moisture condition. The high-moisture condition represents the worst trafficability condition; marshes and other perennially wet, soft areas are examples. Low-lying areas with fluctuating water

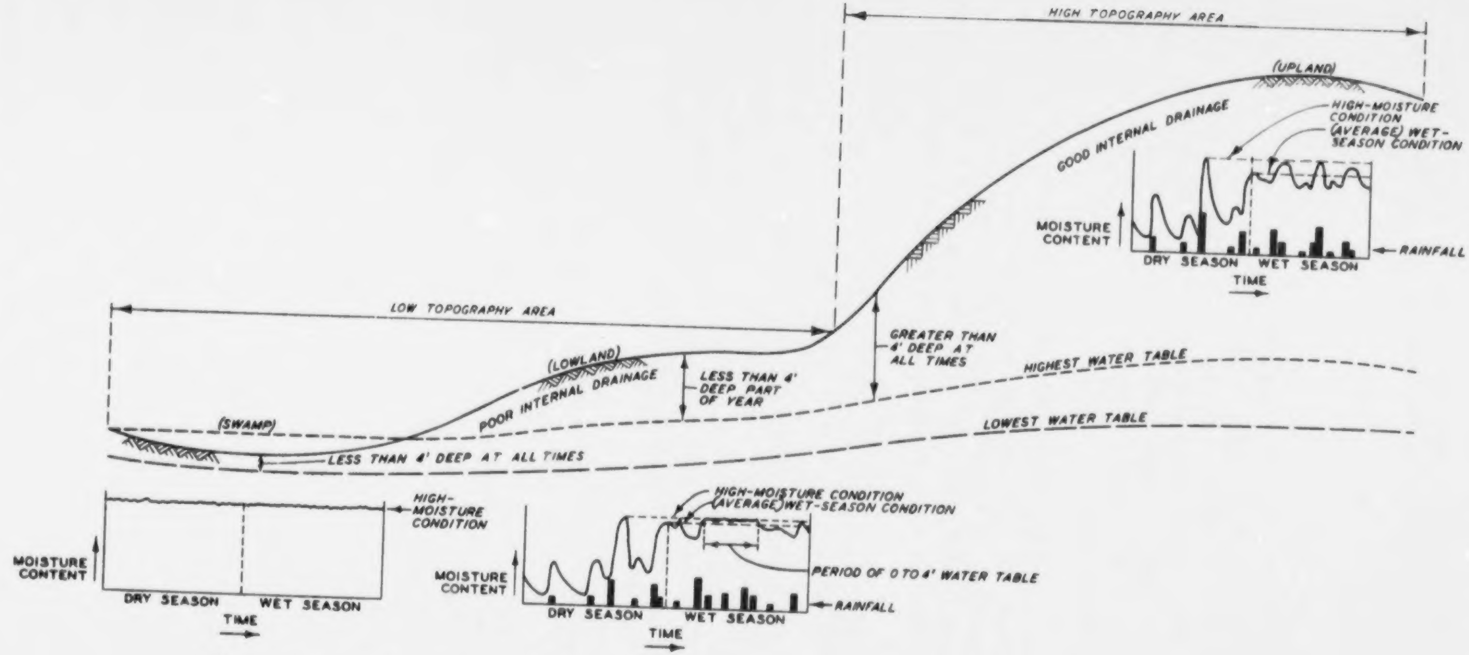

HIGH TOPOGRAPHY AREA
(UPLAND)
GOOD INTERNAL DRAINAGE
HIGH-MOISTURE CONDITION
(AVERAGE) WET-SEASON CONDITION
MOISTURE CONTENT
RAINFALL
DRY SEASON
WET SEASON
TIME
LOW TOPOGRAPHY AREA
(LOWLAND)
POOR INTERNAL DRAINAGE
LESS THAN 4' DEEP PART OF YEAR
GREATER THAN 4' DEEP AT ALL TIMES
HIGHEST WATER TABLE
(SWAMP)
LOWEST WATER TABLE
LESS THAN 4' DEEP AT ALL TIMES
HIGH-MOISTURE CONDITION
MOISTURE CONTENT
DRY SEASON
WET SEASON
TIME
HIGH-MOISTURE CONDITION
(AVERAGE) WET-SEASON CONDITION
PERIOD OF 0 TO 4' WATER TABLE
MOISTURE CONTENT
RAINFALL
DRY SEASON
WET SEASON
TIME

Figure 87. Profile of a typical area showing various topography-moisture conditions during the year.[6]

tables and upland areas with seasonal, perched water tables are examples of low topography where a high-moisture condition occurs intermittently. Low- and high-topography areas that have been subjected to moderate or heavy rainfall are normally under a high-moisture condition during and immediately following rain periods, but a combination of high moisture and high topography has not been included in the data base. A high-moisture condition is considered to prevail at any low-topography site where the water table is known to have been within the top 18 in. This 18-in. criterion is based on studies showing that the decrease in soil strength with the decrease in depth to the water table becomes critical anywhere above a depth of 18 in.

e. Dry-season condition. The dry-season condition has not been distinguished, since it ordinarily presents favorable trafficability. (An exception is that dry sand may immobilize wheeled vehicles with standard tires.) It will suffice to say that landfill cover that performs satisfactorily in wet-season conditions will usually perform even more satisfactorily in dry-season conditions. Accordingly, designing for wet-season trafficability will also cover dry-season trafficability with a degree of conservatism.

Slope Index

Vehicles that can traverse horizontal surfaces often become immobilized when climbing, other things being equal. The immobilizing force is a function of the vehicle weight and the angle of slope. Accordingly, an index for slope is useful as an adjustment in VCI above that for level ground.[6] These excess index points, called slope index (SI), help determine "go" or "no go" when a comparison is made between adjusted VCI and measured RCI of soil. Procedures are available for determining slope effects and are summarized in Figure 88. SI values for tracked and wheeled vehicles can be obtained for a given slope from the curves. If, for example, the slope is 30 percent, SI for the two vehicle classes would be 14 and 20, respectively.

Conversely, an effective rating cone index (ERCI) may be used for rating the trafficability of a sloping soil. The ERCI is computed by subtracting SI from RCI . For example, if the RCI of a soil is 50 and the slope is 30 percent, the ERCI would be 38 (50 minus 14) for tracked vehicles.

USE OF RCI AND VCI FOR DESIGN

The soil trafficability scheme discussed above is directly useful for design purposes. As summarized in Figures 89 and 90, the scheme evaluates soil types in descending order of their median RCI under three conditions of moisture: high topography and low topography under wet-season conditions and low topography under high-moisture condition. Soil types according to both the USCS and the USDA are employed.

Vehicle Categories

A soil that is easily trafficable for one vehicle may be impassable for

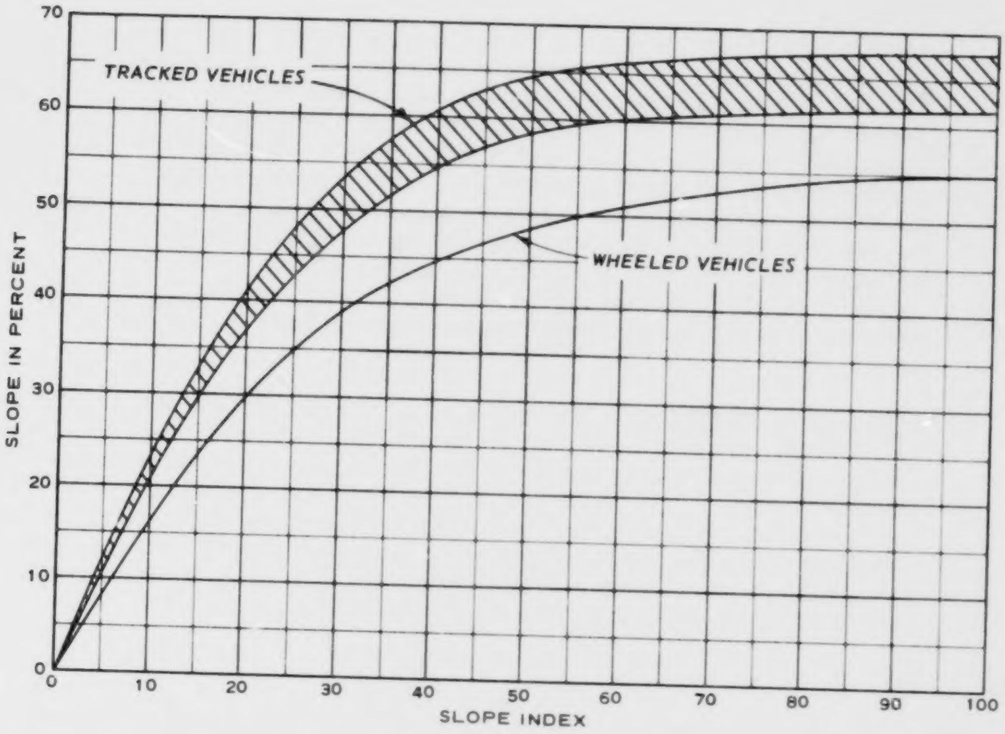


Figure 88. SI for two vehicle classes.[6]

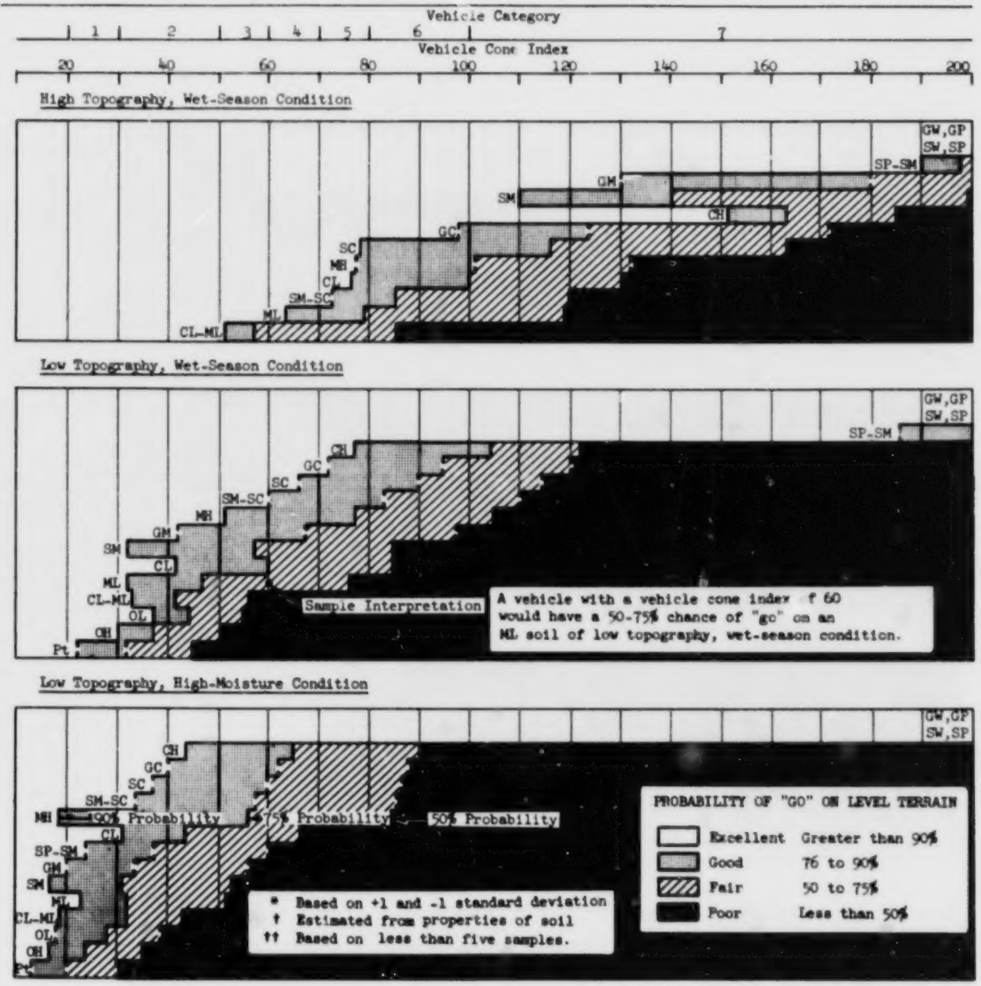
another, and each vehicle has its own minimum soil strength for operation. Therefore, it has been necessary to incorporate vehicle requirements into the scheme for estimating vehicle trafficability. The VCI for individual vehicles within seven broad categories are given in Table 33. Categories 2 through 7 include vehicles commonly used in waste disposal operations.

Soil Trafficability, Level Terrain

Soil trafficability for level terrain is presented in USCS terms for the three moisture-topography conditions in Figure 89. A similar presentation in USDA terms is made in Figure 90. Information for each soil type takes the form of approximations of the probability of "go" on level terrain for various vehicle categories. The percent probabilities of vehicle "go" have been arbitrarily classified as:

Excellent	greater than 90 percent probability of "go"
Good	76 to 90 percent probability of "go"
Fair	50 to 75 percent probability of "go"
Poor	0 to 49 percent probability of "go"

Soil Type Symbol	Strength Measurements Probable Range* CI	 RI	 RCI	Mean RCI
High Topography, Wet-Season Condition				
GW, GP SW, SP	---	---	---	---
SP-SM	125-241	1.19-2.17	196-316	256
GM	---	---	---	230†
SM	130-224	0.77-1.83	137-287	212
CH	167-217	0.84-1.10	158-210	184
GC	---	---	---	165†
SC	127-231	0.72-0.98	104-208	156
MH	151-211††	0.32-1.00††	64-160††	112††
CL	123-211	0.59-0.95	82-180	131
SM-SC	147-185	0.47-1.13	65-211	138
ML	118-224	0.46-1.02	67-189	128
CL-ML	111-209	0.44-0.72	54-136	95
Low Topography, Wet-Season Condition				
GW, GP SW, SP	---	---	---	---
SP-SM	300	0.94	282	282†
CH	98-194	0.74-1.14	81-193	137
GC	---	---	---	130†
SC	97-257††	0.59-1.21††	61-255††	158††
SM-SC	160-216††	0.45-1.31††	72-208††	140††
MH	94-170	0.51-0.99	48-162	105
GM	---	---	---	125†
SM	109-217	0.29-1.03	34-188	111
CL	90-188	0.46-0.88	46-146	96
ML	102-200	0.27-0.81	34-134	84
CL-ML	85-165	0.3[illegible].69	34-96	65
OL	95-135	0.38-0.74	41-89	65
OH	64-164	0.32-0.78	14-110	62
Pt	76-90††	0.45-0.67††	41-51††	46††
Low Topography, High-Moisture Condition				
GW, GP SW, SP	---	---	---	---
CH	69-167	0.64-1.02	48-146	97
GC	---	---	---	90†
SC	---	---	---	88†
SM-SC	150-182††	0.45-0.63††	66-98††	82††
MH	83-151	0.46-0.92	43-123	83
CL	71-165	0.42-0.80	39-117	78
SP-SM	---	---	---	74†
GM	---	---	---	72†
SM	81-183	0.15-0.87	12-126	69
ML	81-171	0.26-0.60	22-88	55
CL-ML	71-155	0.27-0.53	26-66	46
OL	87††	0.56††	49††	49††
OH	42-132	0.26-0.66	21-49	35
Pt	76-90††	0.45-0.61††	41-51††	46††

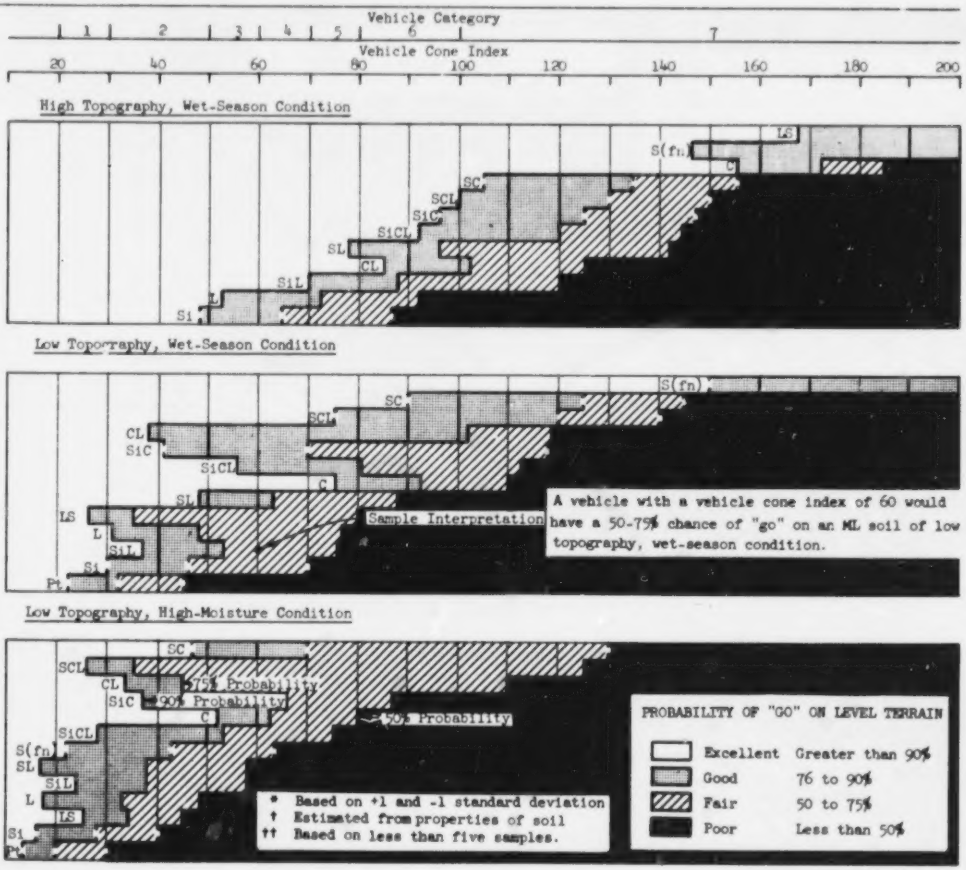


A vehicle with a vehicle cone index of 60 would have a 50-75% chance of "go" on an ML soil of low topography, wet-season condition.

* Based on +1 and -1 standard deviation
† Estimated from properties of soil
†† Based on less than five samples.

Figure 89. Soil trafficability in USCS terms.[6]

Soil Type Symbol	Strength Measurements Probable Range* CI	RI	RCI	Mean RCI
High Topography, Wet-Season Condition				
LS	135-249	1.16-1.80	201-300	254
S(fn)	130-218	1.18-2.12	190-300	251
C	167-227	0.80-1.14	159-219	189
SC	---	---	---	161†
SCL	137-229	0.74-0.96	110-202	156
SiC	125-163††	0.23-1.17††	23-187††	105††
SiCL	156-208	0.66-0.94	108-188	148
SL	122-204	0.42-1.46	81-215	148
CL	114-180	0.77-0.97	86-172	129
SiL	126-222	0.54-0.88	76-172	124
L	106-190	0.51-0.87	63-147	105
Si	202††	0.54††	108††	108††
Low Topography, Wet-Season Condition				
S(fn)	212-300††	0.79-1.81††	278-300††	291††
SC	---	---	---	150†
SCL	113-237	0.60-0.98	92-180	136
CL	95-211	0.57-1.01	69-175	122
SiC	85-197	0.67-1.07	66-184	125
SiCL	100-196	0.59-0.99	62-180	121
C	80-180	0.72-1.20	68-176	122
SL	111-195	0.32-1.10	46-168	107
LS	111-241	0.24-0.84	20-188	104
L	89-181	0.40-0.90	37-143	90
SiL	96-190	0.38-0.76	41-125	83
Si	49-237††	0.40-0.48††	27-101††	64††
Pt	76-90††	0.45-0.67††	41-51††	46††
Low Topography, High-Moisture Condition				
SC	---	---	---	115†
SCL	66-204	0.60-0.90	44-172	108
CL	71-209	0.54-0.96	51-159	105
SiC	60-176	0.66-0.98	44-152	98
C	66-138	0.64-1.12	50-126	88
SiCL	70-164	0.54-0.86	44-120	82
S(fn)	---	---	---	74†
SL	87-177	0.19-0.85	24-110	67
SiL	78-166	0.33-0.67	36-100	68
L	68-150	0.34-0.72	28-86	57
LS	87-177	0.22-0.68	12-110	61
Si	59-133††	0.38-0.50††	30-52††	41††
Pt	76-90††	0.45-0.67††	41-51††	46††



A vehicle with a vehicle cone index of 60 would have a 50-75% chance of "go" on an ML soil of low topography, wet-season condition.

* Based on +1 and -1 standard deviation
† Estimated from properties of soil
†† Based on less than five samples.

Figure 90. Soil trafficability in USDA terms.[6]

TABLE 33. CATEGORIES AND VCI OF VEHICLES[108-111]

Category	VCI Range	Vehicle Types
Low ground pressure	29 or less	Tractors designed for very low ground pressure. Examples: VCI of D4D LGP, D5 LGP, and D6C LGP all = 17 approximately.
2	30 - 49	Tractors with comparatively wide tracks and low contact pressures. Examples: VCI of D7 tractor = 38, D4 tractor = 49, IH model TD 20-200 tractor = 36.
3	50 - 59	Tractors with average contact pressures and some trailed vehicles with very low contact pressures. Example: VCI of D8 tractor (old model) = 50.
4	60 - 69	Most tractors with high contact pressures, and all-wheel-drive trucks and trailed vehicles with low contact pressures. Example: VCI of 2-1/2-ton, 6 by 6 dump truck = 62.
5	70 - 79	Most all-wheel-drive trucks and many trailed vehicles. Example: VCI of 1-1/2-ton, 4 by 4 dump truck = 73.
6	80 - 99	Many all-wheel-drive and rear-wheel-drive trucks and trailed vehicles intended primarily for highway use. Example: VCI of 1/2-ton, 4 by 2 pickup truck = 88.
7	100 or greater	Rear-wheel-drive vehicles and others that generally are not expected to operate off roads, especially in wet soils. Example: VCI of 5-ton, 4 by 2 dump truck = 119.

Figures 89 and 90 are based on a comprehensive program of trafficability testing[6] with cone penetrometer data from 767 sites in 41 states, generally located in the humid, temperate regions of the United States. A few sites were located in subhumid or arid climatic areas wherein water contents were similar to wet-season water contents in the humid, temperate regions. The study established sample statistics of strength indexes (e.g., see Figure 86 for RCI).

The VCI's corresponding to 50, 75, and 90 percent probabilities of "go" were derived from cumulative frequency graphs of the RCI data (not shown; see Reference 6). For example, from a frequency graph for CL soil at low-topography, high-moisture condition, RCI's at 50, 75, and 90 percent cumulative frequencies were found to be 74, 50, and 39, respectively. Lines delineating the vehicle probability of "go" on the bar graphs in Figures 89 and 90 are solid where based on five or more samples and judged to be most reliable. Broken lines indicate that less than five samples were used or the data were otherwise questionable.

The figures may be used to estimate the probability of "go" (or "no go") given a specific USCS or USDA soil and a specific piece of solid waste and/or soil handling equipment. The example in Figure 89 indicates that a vehicle with VCI of 60 has probability of about 60 percent (within 50 to 75 percent) of "go" on a ML soil (RCI averaging 84) at low-topography, wet-season condition. If this probability is considered unacceptable, contingency precautions should be outlined or a more trafficable soil should be used for the cover.

Design Adjustment for Slope

The design procedure outlined under Soil Trafficability, Level Terrain above will need to be adjusted where slopes are involved. The procedure for reducing RCI to ERCI or for increasing VCI has been described under Slope Index above.

Soil Slipperiness and Stickiness Effects

Guidance in predicting slipperiness and stickiness of available soil types on the basis of experience[6] is presented in Table 34. Severe slipperiness will often immobilize wheeled vehicles that are not equipped with special traction devices and, in combination with relatively low RCI (a few points above VCI), will often cause even chain-equipped wheeled vehicles to become immobilized. Slipperiness may reduce control of tracked vehicles but will seldom immobilize them. Soils designated as having moderate to severe stickiness (Table 34) will, when wet, cling to a vehicle's running gear and may accumulate detrimentally. Soil slipperiness and stickiness, best considered as subordinate factors in designing for cover trafficability, are involved in choosing soil (Table 34) or special procedures only when other considerations are about equal.

DESIGNING FOR TRAFFICABILITY

The foregoing discussion provides guidance for analyzing cover for adequate trafficability. However, trafficability will seldom be primary in cover design, nor will manipulation of soil type be cost-effective. Special designs and operational procedures are usually the better approach.

Soil Selection

Figure 86 provides a useful summary of relative effectiveness of soil types based on RCI . In rare cases, it may be reasonable to consider importing soil where the figure predicts poor performance from the intended cover soil. Supplies of best material, such as sand, where limited, can be saved for selected use, e.g., along haulage routes.

Site Configuration

The designer has latitude to arrange the site in such a way as to facilitate trafficability. Choosing high ground certainly helps. Most landfills with relief greater than a few feet can be sloped to promote runoff and keep soil moisture relatively low.

TABLE 34. EFFECTS OF SLIPPERINESS AND STICKINESS OF SOILS IN LOW-TOPOGRAPHY, WET-SEASON CONDITION[6]

USCS Soil Type	Effects of		USDA Soil Type*	Effects of	
	Slipperiness	Stickiness		Slipperiness	Stickiness
GW, GP, SW, SP	None	None	S(fn)	None	None
SP-SM	None	None	SC	Moderate	Moderate
CH	Severe	Severe	SCL	Moderate	Moderate
GC	Moderate	Moderate	CL	Moderate	Moderate
SC	Moderate	Moderate	SiC	Severe	Severe
SM-SC	Slight	None	SiCL	Moderate	Moderate
MH	Severe	Moderate	C	Severe	Severe
GM	Slight	None	SL	Slight	Slight
SM	Slight	None	LS	Slight	None
CL	Moderate	Moderate	L	Moderate	Moderate
ML	Moderate	Slight	SiL	Moderate	Moderate
CL-ML	Moderate	Slight	Si	Moderate	Slight
OL	Moderate	Slight	Pt	Moderate	Slight
OH	Moderate	Slight			
Pt	Moderate	Slight			

* Abbreviations for USDA types are S sand, C clay, L loam, and Si silt.

Drainage Ditches

Ditches serve the same purposes as manipulation of site layout, i.e., they remove water quickly and reduce infiltration. Traffic routes deserve high priority.

Equipment Changes

Use RCI in design to choose other equipment of relatively lower VCI during wet seasons or periods. Such substitution may even be possible on an unscheduled basis. Elsewhere, supplement wheel traction by adding chains or by switching to tracks.

Flatter Slopes

Another operational procedure for periods of inclement weather and poor trafficability is to arrange routing so as to eliminate slope climbing for haulage vehicles. The operator may reroute the traffic temporarily so that all but a short dumping segment moves downgrade. A level traverse may also be effective.

Stabilized Soil

Fly ash, lime, or cement can be used to increase strength and reduce permeability of the traffic-carrying cover soil. It is recommended that special attention be directed to testing fly ash for acceptability where available as waste in the region.

Lime Additions

Add lime during wet conditions to haul roads and to facilitate cover manipulation. Lime is superior to cement for this purpose, and about 2 percent might be tried as a first cut. In effect the PI is reduced by an increase in PL , and the soil condition should change beneficially from plastic to semisolid.

Semipermanent Distribution Routes

The on-site handling and covering operation should be arranged so that vehicles with potential trafficability problems are confined to limited paths designed and maintained for trafficability. Indigenous or imported granular soils, base courses, and/or inexpensive pavements should be considered to prepare a distribution route for use during the operations at one level, for example.

Daily Maintenance

Daily maintenance may be established and equipment made available to assure that deterioration in cover trafficability is rectified before becoming disruptive. As a first approach, it may be effective to assign municipal or other road grading equipment and a crew to half-day maintenance periods at intervals of 2 to 5 days to add supplemental soil, then sprinkle, smooth, and compact. The on-site equipment should be sufficient to take care of rutting and other trafficability problems that arise during daily operation. Stockpiles of suitable additive material (granular, clayey, etc.) should be kept on hand or be readily available.

Special Wet-season Area

The disposal area should be organized in such a way as to have a standby section available for use during periods of inclement weather. This section might be laid out on well-drained sandy terrain near arterial access and be composed of single-height waste cells where likelihood of trafficability problems is minimal.

Special Waste Compaction

It is anticipated that cover trafficability may become a problem where high degrees of compaction of solid waste are not achieved. Deep, immobilizing ruts may develop as a consequence of spongy waste "subgrade" rather than deficiencies of the cover soil. Attempts to reduce this problem may be made by increasing the waste compaction effort. One might also consider increasing the ratio of soil to waste in the covering operation.

Reduced Thickness

Some experienced operators find that reducing the soil cover thickness improves trafficability in wet conditions. Presumably, the solid waste provides better traction here.

SECTION 15

DEWATERING AND CONSOLIDATING SATURATED WASTE

Certain solid wastes from treatment of industrial and municipal wastewater are disposed in a saturated condition as sludges and slurries. It will often be advantageous to speed up the removal of contained water in a controlled manner, and certain cover materials can function effectively here.

Particularly troublesome solid wastes are those that tenaciously hold the included water and tend to remain in a plastic or liquid state indefinitely. Examples are paper-mill sludges[11] and clay slurries from phosphate mining. A pollution potential of the interstitial water compounds the problem.

SLUDGE/SLURRY CONSOLIDATION

Sludges and slurries ordinarily are fully saturated, yet most of the water is not bound strongly to the solids. Therefore, consolidation properties are like those of saturated fine-grained soils. A useful reference[11] has been abstracted in the following.

Formulation of Consolidation Process

If saturated material is loaded one-dimensionally (see CONSOLIDATION TEST in Section 3), the decrease in volume is accomplished by water being squeezed from the voids at a rate controlled by the sludge permeability. The change in height ΔH , per unit of original height, equals the change in volume per unit of original volume. When volume change is expressed in terms of void ratio, ΔH becomes

$$\Delta H = H_1 \left(\frac{\Delta e}{1 + e_1}\right) = H_1 \left(\frac{e_1 - e_2}{1 + e_1}\right) \qquad (20)$$

Secondary compression occurs after this primary compression and may be related to plastic creep and compression of the constituent particles; it is not considered pertinent here. The rate of consolidation can also be calculated, though accuracy is reduced by changing consolidation parameters, secondary compression, and construction rate (increasing load rate).

Vertical Stresses

The vertical stress acting on a horizontal plane at depth z is equal to the weight of all matter that rests above the plane. A load-depth diagram is usually constructed by plotting stress versus depth as in the example in Figure 91. As a result of the hydrostatic pressure, the effective contact stress between sludge particles is reduced by the magnitude of u (Figure 91). The average vertical stress within a layer may be taken at the mid-depth point with negligible error (about 10 percent). The average effective stress in the sludge layer is $P_o' = 138\ \text{lb/ft}^2$ in the example.

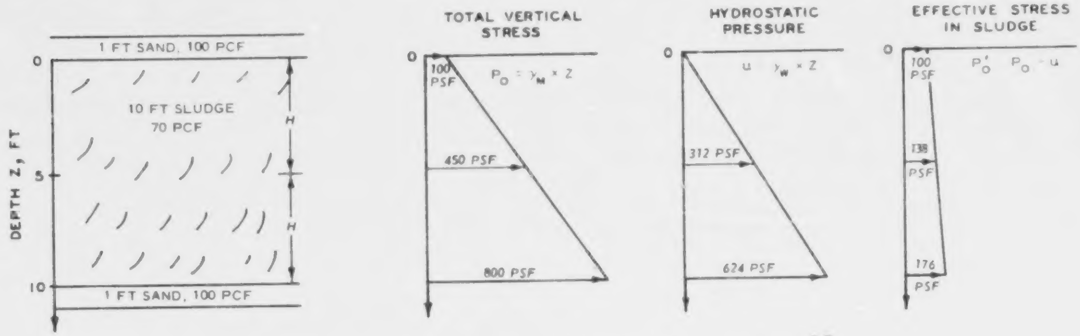

1 FT SAND, 100 PCF
0
10 FT SLUDGE
70 PCF
H
5
H
10
1 FT SAND, 100 PCF
DEPTH Z, FT
TOTAL VERTICAL STRESS
0
100 PSF
$P_o = \gamma_M \times Z$
450 PSF
800 PSF
HYDROSTATIC PRESSURE
0
$u = \gamma_w \times Z$
312 PSF
624 PSF
EFFECTIVE STRESS IN SLUDGE
0
100 PSF
$P_o' = P_o - u$
138 PSF
176 PSF

Figure 91. Example load-depth diagram.[11]

Primary Settlement Calculation

Settlement of a slurry/sludge landfill can be predicted once consolidation test results (see Section 3) are available.[11] Wet unit weight is available by testing, and the average initial P_o' for each sludge layer can be calculated (Figure 91). The total load ΔP above each layer is the wet weight of all sludge, sand, and surcharge layers above the one being considered. The primary settlement for a layer is computed as

$$\Delta H = \frac{C_c H_t}{1 + e_o} \left(\log_{10} \frac{P_o' + \Delta P}{P_o'} \right) \tag{21}$$

where C_c = compression index determined at P' (see Section 3)
H_t = total initial thickness of the sludge layer. In Figure 91, $H_t = 2H$
e_o = initial void ratio existing at P_o'

Consolidation Time

According to the widely accepted calculation of Terzaghi, the time required to reach a given percent consolidation is

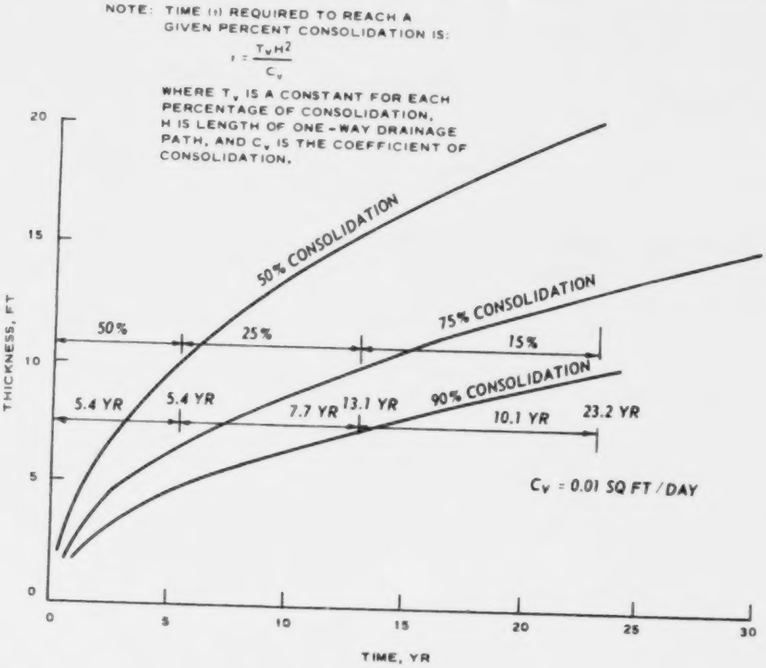
$$t = \frac{T_v H^2}{c_v} \tag{22}$$

where H = thickness or length of one-way drainage

T_v = a time factor varying with degree of consolidation
c_v = coefficient of consolidation

T_v is determined from existing charts.[11] The c_v is considered a soil property although it depends also upon effective stress. A laboratory test is needed to establish a specific value of c_v as explained in Reference 12.

The effects of t and H and the degree of consolidation achieved are illustrated in Figure 92 for a clay with very low c_v. If the soil is underlain by impervious material and escaping water must flow to the surface, H is the total thickness of sludge/slurry. Alternatively, if drainage layers intervene as would be the case where sand is placed intermittently as cover, the thickness H is one-half their vertical interval. Obviously, H has a great effect on time to desired consolidation.



NOTE: TIME (t) REQUIRED TO REACH A GIVEN PERCENT CONSOLIDATION IS:

$$t = \frac{T_v H^2}{C_v}$$

WHERE T_v IS A CONSTANT FOR EACH PERCENTAGE OF CONSOLIDATION, H IS LENGTH OF ONE-WAY DRAINAGE PATH, AND C_v IS THE COEFFICIENT OF CONSOLIDATION.

Figure 92. Effect of thickness on consolidation of dredged material.[51] (Specific example is for H = 10 ft.)

DESIGNING FOR DEWATERING AND CONSOLIDATING

From principles above and in Section 3, it is a logical step to consider designing rapid stabilization of a landfill of sludge or slurry by choice of cover or incorporation of features for increasing rate of drainage (Figure 93). Several techniques are recommended.

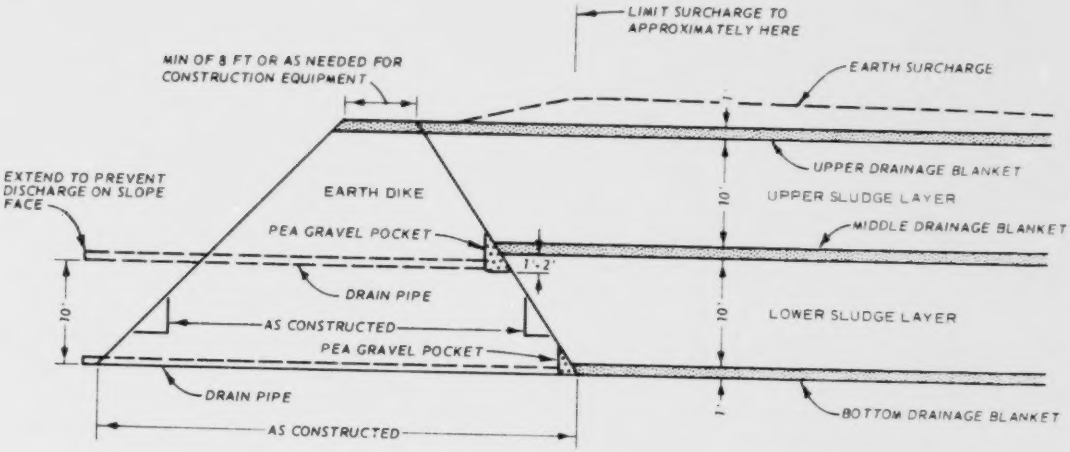

LIMIT SURCHARGE TO APPROXIMATELY HERE
MIN OF 8 FT OR AS NEEDED FOR CONSTRUCTION EQUIPMENT
EARTH SURCHARGE
1'
UPPER DRAINAGE BLANKET
EXTEND TO PREVENT DISCHARGE ON SLOPE FACE
EARTH DIKE
10'
UPPER SLUDGE LAYER
PEA GRAVEL POCKET
MIDDLE DRAINAGE BLANKET
1'-2'
DRAIN PIPE
10'
AS CONSTRUCTED
10'
LOWER SLUDGE LAYER
PEA GRAVEL POCKET
DRAIN PIPE
1'
BOTTOM DRAINAGE BLANKET
AS CONSTRUCTED

Figure 93. Dike and sludge cross section.[11]

Clean Sand

Clean sand with its inherently high k is an obvious material for cover intended ultimately to drain sludge and slurry solid wastes. The USCS type recommended first is SP. Granular wastes may be substituted locally.

Reduced H Value

The most effective way of speeding the dewatering and stabilization of sludge/slurry is to reduce H, e.g., by incorporating intermediate drainage layers. Design H on the basis of c_v from consolidation testing and the t value specified for the project.

Collector Pipes

Drainage layers normally develop large pore pressures that render them ineffective unless collector pipes are provided.[51] Gravity drainage to the surface through side slopes (Figure 93) is especially effective. Such gravity drains are complicated by the necessity to have sufficient inclination to account for anticipated settlement.

Special Equipment

Application and spreading of cover over sludge or slurry will usually encounter extreme problems of bearing capacity. Special LGP equipment exerting only low ground pressure may be necessary (see Section 14 and Reference 111).

SECTION 16

COLD CLIMATE OPERATIONS

In Alaska, the northern tier of states, and the mountainous regions, daily mean air temperatures fall below freezing frequently or for extended periods of days or even weeks during the winter. The ground freezes to depths of several inches or a few feet, and measures to counteract or reduce freezing/thawing disturbance and other effects on cover soils may be necessary.

PHENOMENA OF COLD CLIMATES

The phase change from water to ice results in an increase in volume of about 9 percent. If water occupies all pores in a granular (nonfrost susceptible) soil, the overall volume increase upon freezing depends on the relative volumes of water and soil particles, but it will be considerably less than 9 percent. Frost heave that occurs under these circumstances is minor in the overall problem of severe frost action.

The phenomena involve the migration of water to a freezing front from the unfrozen soil or waste to form distinctive layers, lenses, or veins of ice, which may add significantly to the original water content of the cover soil. Fortunately, the potential for serious damage requiring costly repairs in a landfill operation are relatively minor. Careful selection of cover soil and incorporation of design features and orderly operating procedure should reduce the seriousness of frost action.

Freezing Index

A widely used method of quantifying the severity of cold climate is with the freezing index.[112] The index is computed in degree-day units by summing cumulatively the values for each day over a freezing season. The daily values are simply the differences in mean air temperature and freezing temperature (32°F).

Figure 94 shows freezing indices for the conterminous United States for the coldest year in a 10-year cycle or the average of the three coldest in a 30-year cycle. The nearly 400 U. S. Weather Bureau stations that were used for basic data are spotted in the figure. A site-specific design freezing index should be used in preference to those in the figure wherever nearby stations are available because differences in elevation and topographic position and nearness to cities, bodies of water, or other sources of heat, produce considerable variations in the index over short distances. These

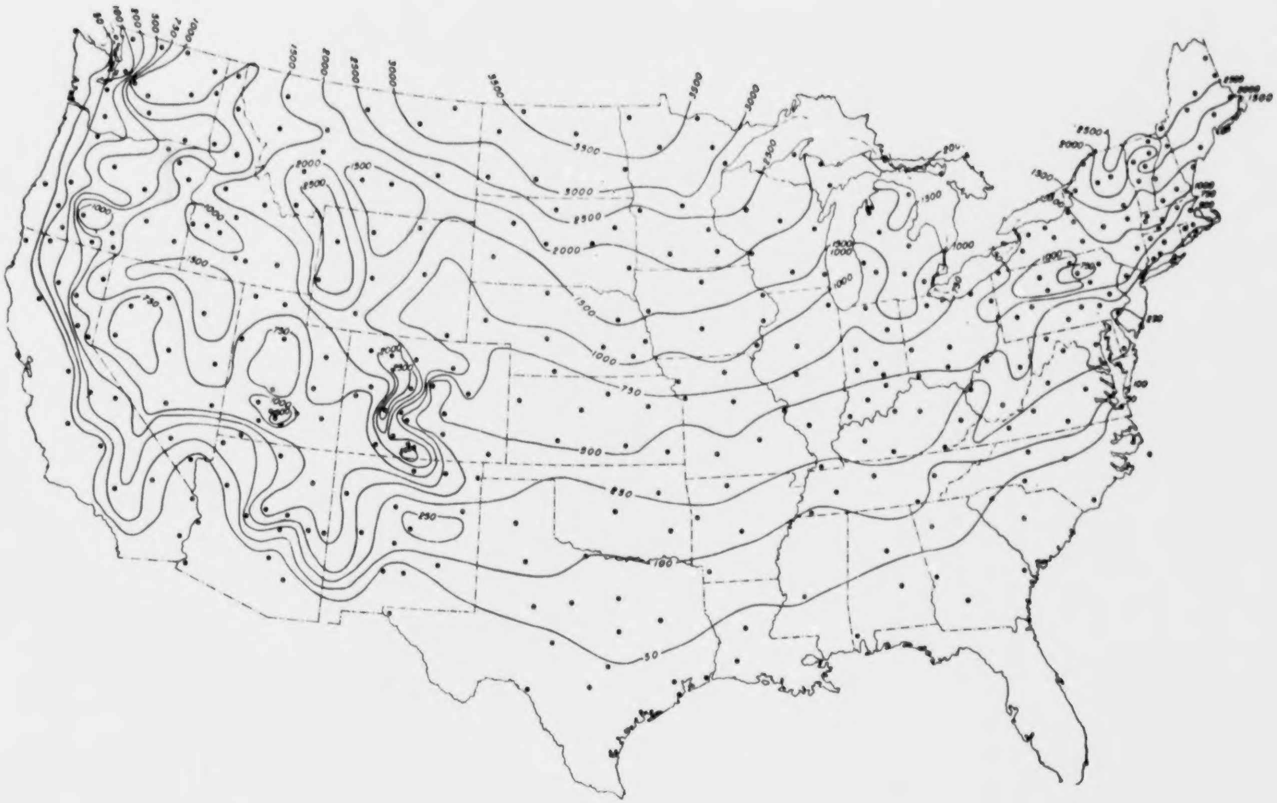

3500
3000
2500
2000
1500
1000
750
500
250
100
50

Figure 94. Design freezing index values for the conterminous United States.[113]

variations are particularly important to design in areas of indices of less than 1000, i.e., in much of the United States.

Frost Depth

The maximum depth of frost penetration can be predicted in a general way on the basis of the freezing index. For example, Figure 95 shows generalized curves for a direct relationship at various soil conditions. Figure 96 shows a recent map of mean depth of frost penetration. This information should be helpful in choosing thickness for various final cover soils and in choosing other design measures outlined at the end of this section.

Since much of the importance of frost action at solid waste operations concerns daily cover, it is appropriate to consider applying the freezing index for periods of one or a few days rather than an entire cold season. The index applies on a daily basis also, in a very approximate way. For example, an unfrozen silty sand placed on solid waste may be expected to freeze to a depth of 20 cm during 10 days in which the mean daily temperature is 22°F (Figure 95).

Snow Depth

Provisions should be made in planning and design for expected heavy accumulations of snow (Figure 97). Total snowfall data are available for the numerous U. S. Weather Bureau stations. Values from nearby stations are sufficiently site-specific except in mountainous areas where large changes in elevation over a short horizontal distance may result in large differences in snowfall. Accordingly, local adjustments in the predictions of snowfall should be made in mountainous areas.

WINTER PROBLEMS AT LANDFILLS

Several problems may develop as a direct consequence of cold climate during the operation and life of a waste disposal area. A careful review of general winter practices in the region, along with consideration of soil availability, economic limitations, and environmental restraints should help rank potential problems and aid in selecting the best materials available.

Frozen Waste

Garbage wastes tend to resist freezing as decomposition takes place. However, inert solid wastes that are rich in water may freeze after exposure of only a few hours on the ground surface. Further distribution and compacting will be accomplished with difficulty, if at all, and such material will be buried in a frozen condition. The subsequent thawing of frozen waste may have an indirect, disrupting effect on cover and may even compromise its general function of sealing the waste.

Snow Interference

The daily operation at a landfill may be interrupted occasionally by heavy snowfall. Also, it may be unreasonable to clear accumulations of snow,

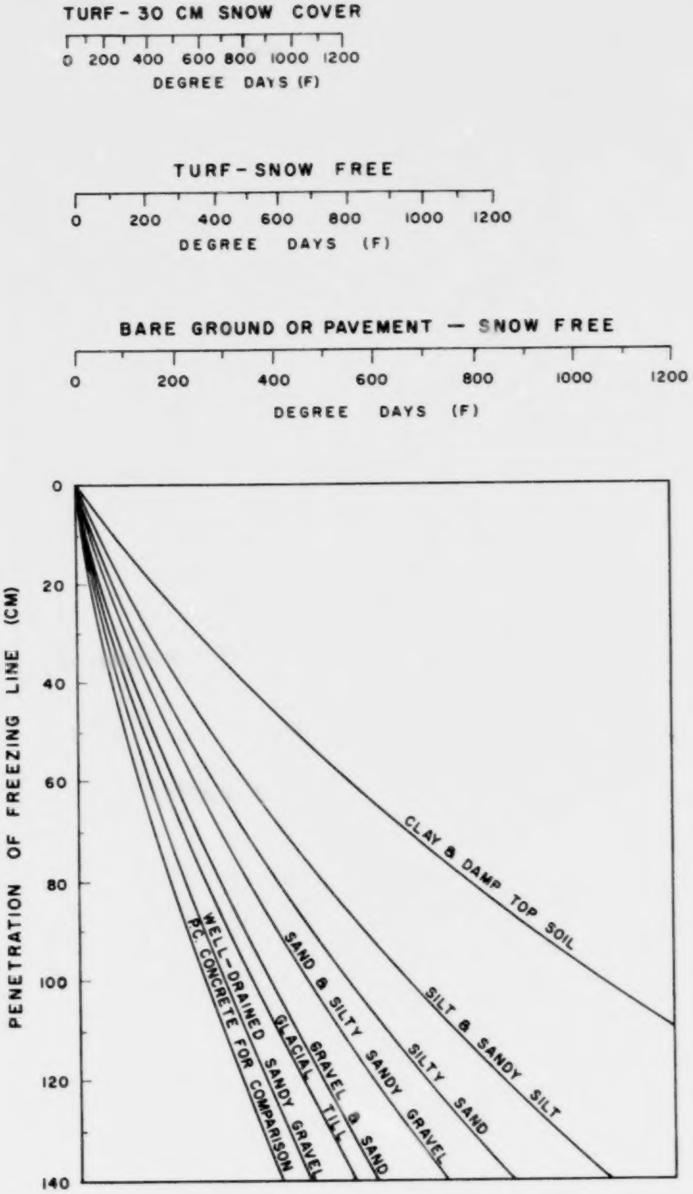


Figure 95. Depth of freezing penetration into soils with bare or covered surfaces.[112]

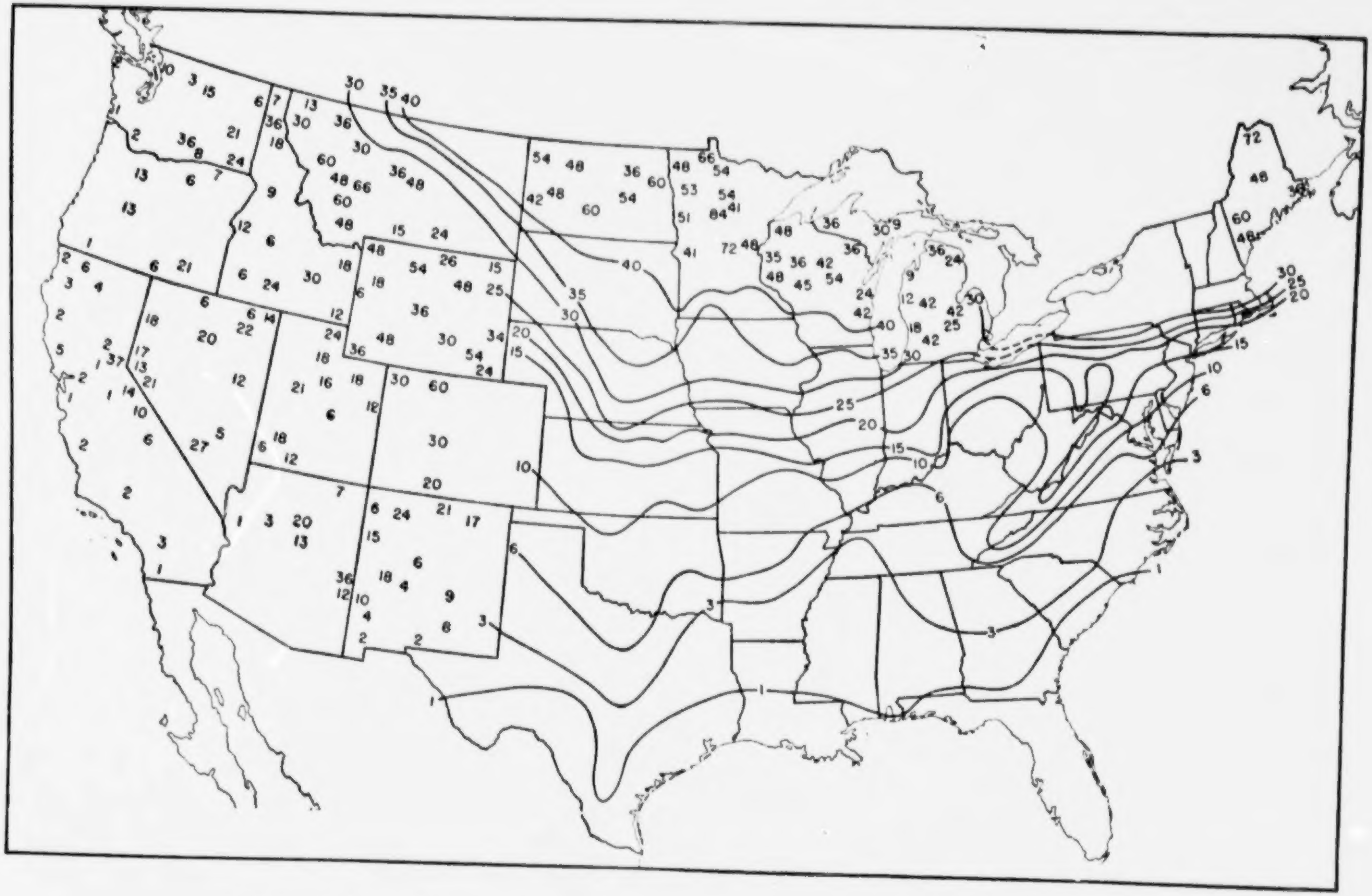

30
35
40
25
20
15
10
6
3
1

Figure 96. Regional depth of frost penetration (in inches).[79]

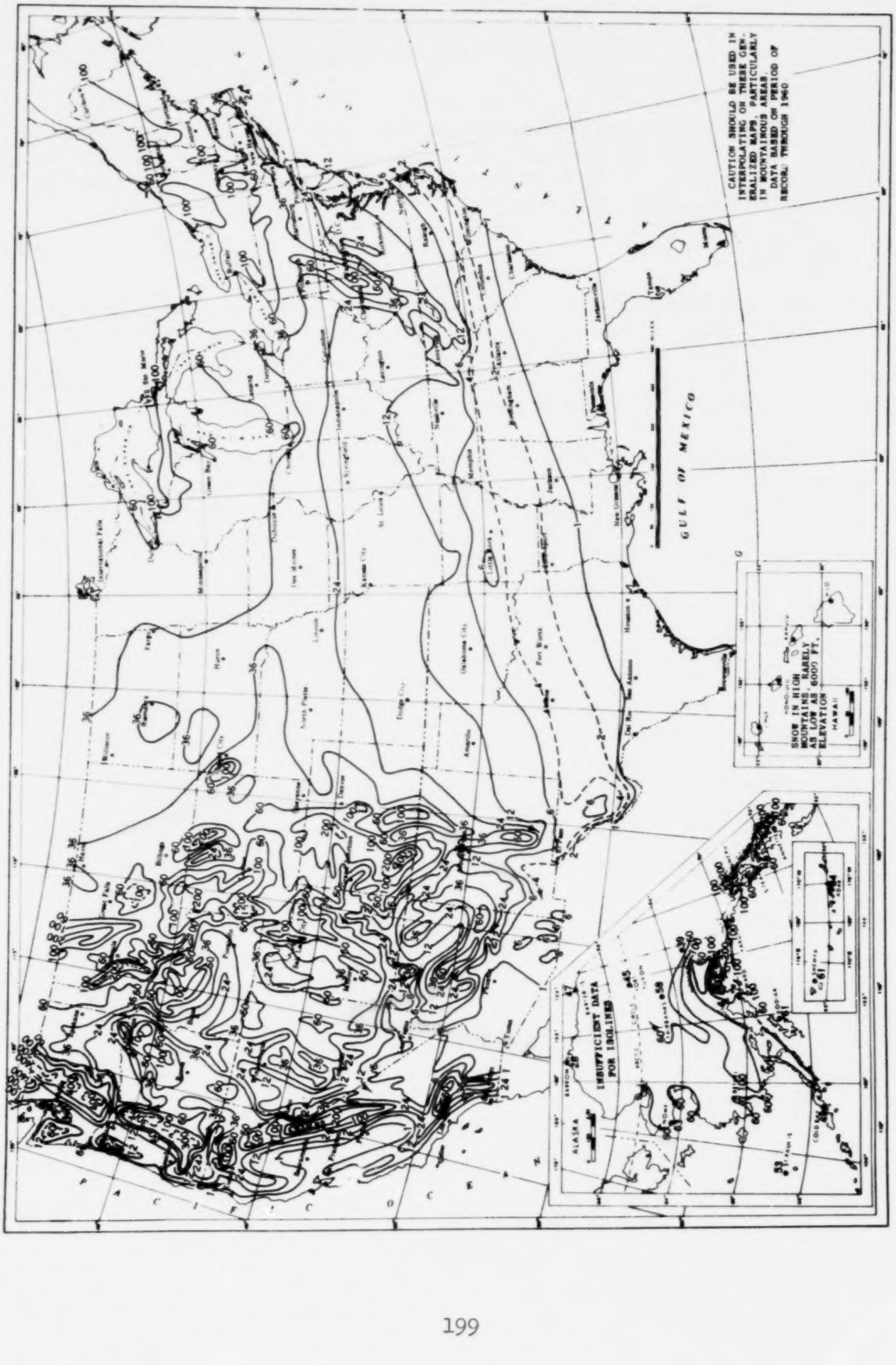

CAUTION SHOULD BE USED IN INTERPOLATING ON THESE GENERALIZED MAPS, PARTICULARLY IN MOUNTAINOUS AREAS.
DATA BASED ON PERIOD OF RECORD THROUGH 1960
GULF OF MEXICO
PACIFIC OCEAN
ALASKA
INSUFFICIENT DATA FOR ISOLINES
SNOW IN HIGH MOUNTAINS, RARELY AS LOW AS 6000 FT. ELEVATION
HAWAII

Figure 97. Mean annual total snowfall (in inches).

and as a result, snow and ice may be incorporated in the cover and waste. Allowance should be made for this additional moisture in the landfill. In extreme cases where rapid covering of frozen material provides insulation, a frozen stratum may remain for months into warmer weather when thawing may cause unexpected subsidence.

Apparently, a more common occurrence than snow burial and preservation, however, is the melting of snow on the surface of garbage waste as a result of heat of decomposition.[7] The exothermic effects are most pronounced in the first year. The potential for unwanted infiltration can be serious.

Frozen Cover Soil

Supplying unfrozen cover soil may be difficult during severely cold weather. Cover soils that are frozen when removed from the borrow source may not be compactible to the extent desired by design. If the soil is available only in frozen, solid or blocky form, it may be unreasonable and uneconomical to reduce grain size sufficiently for effective covering.

Three factors determine whether a source of cover soil will be susceptible to hard freezing and the formation of blocky lumps: soil grain size, conditions of drainage, and exposure and insulation. Figure 95 indicates that fine-grained clay and damp topsoil freeze to only about half the depth that gravel and sand do under similar conditions.

Frost Heave

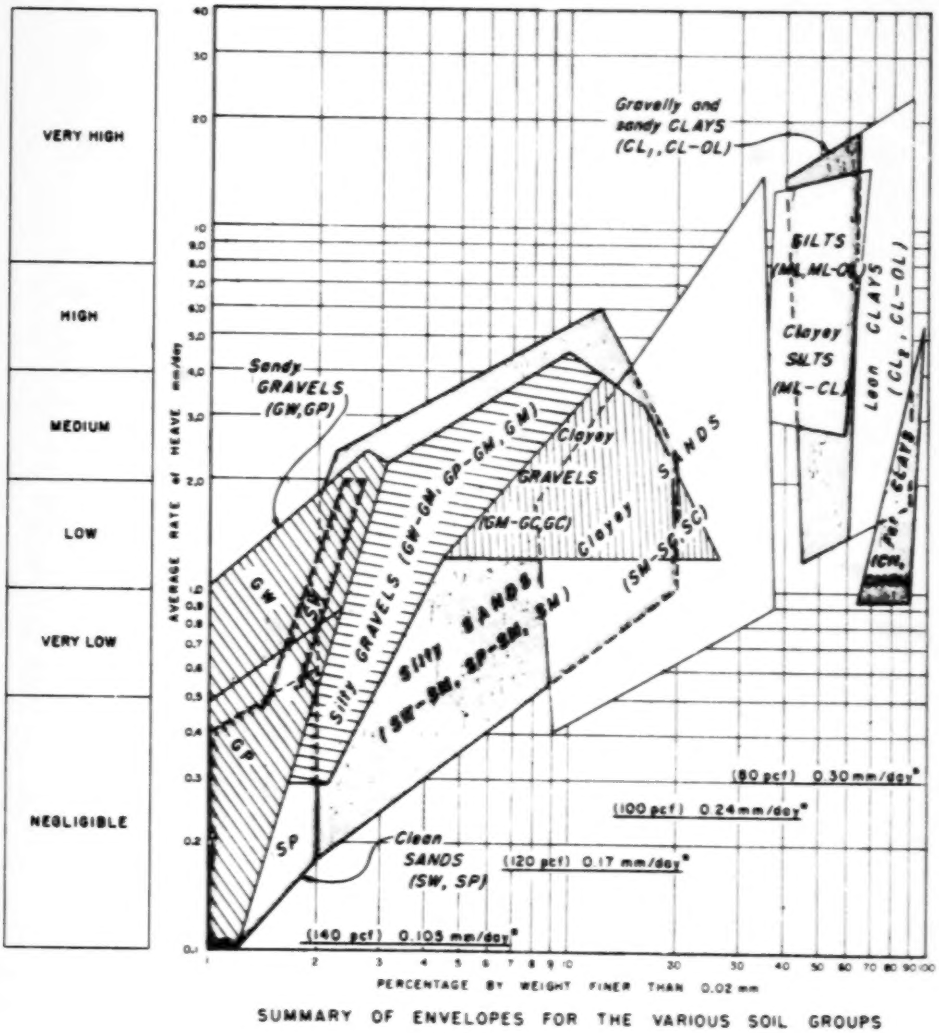
In the context of landfilling, frost heave has a short-term effect in seasonal disruption of the cover and a long-term effect arising at such time as the landfill is used as a foundation for pavements or light structures. The severity of frost heave damage in Arctic climates has led to efforts to establish indicators of frost heave susceptibility.[114] Actual tests on numerous soils have provided information on heave rate according to the percentage of silt and clay size material.[115] Figure 98 indicates that heave rate increases conspicuously from gravel to sand to silt. A less severe heave rate apparently characterizes come clays in comparison with silt.

Slope Sliding

Frozen ground conditions may be detrimental to the stability of landfill slopes during periods of thawing. A layer of saturated soil with little or no strength may develop to a depth of a few feet over a frozen base. Such a development can create an unstable zone that may slide easily (see Section 13).

DESIGNING FOR COLD CLIMATE

Several landfill design recommendations follow from the operations problems identified above.



NOTES: Standard tests performed by Arctic Construction and Frost Effects Laboratory; specimens 6 in. dia by 6 in. high, frozen at penetration rate of approximately 0.25 in per day, with free water at 38°F continuously available at base of specimen. Specimens compacted to 95% or better of applicable standard, except undisturbed clays. Saturations before freezing generally 85% or better.

* Indicated heave rate due to expansion in volume, if all original water in 100% saturated specimen were frozen, with rate of frost penetration 0.25 inch per day.

Figure 98. Rates of heave as related to silt-clay content.[115] (Reproduced by permission of Transportation Research Board.)

Selection of Soil

Soils available as cover should be carefully evaluated in regard to susceptibility to undesirable frost actions. Figure 98 serves as a criterion for selection where the primary concern is for frost heaving. Gravels and sands are obviously the best material for resisting heave. Where problems are anticipated with poor workability during winter operations, coarse-grained soils should be preferred provided they are well drained. Coarse soils drain freely and should retain less water to act as a cementing agent when frozen. The only disadvantage of coarse soils is their tendency to freeze quicker and to greater depths than fine-grained soils; to avoid freezing to great depth, finer soils should be chosen.

Unfrozen Soil Supply

A supply of unfrozen cover material is advantageous, but stockpiling under cover may not be feasible. A more economical way of reserving unfrozen soil is in a relatively thick borrow area. At such a source, a layer of snow and/or frozen soil may be used as insulation, to be removed only as the cover material is needed. Also, a special source of suitable texture and configuration might be reserved for use during especially cold periods or in the middle of the freezing season.

Drainage

Drainage of borrow areas will help to reduce the problem of freezing and formation of blocky and unmanageable cover soil. Surface grading to slope and excavation of ditches or trenches should be sufficient in most cases, but these drainage features should be constructed well before the freezing season begins.

Additives

Additives for reducing frost action (particularly frost heave) fall into four groups:[116] void pluggers and cements, flocculants, dispersants, and waterproofers. Well-graded soils with coarse particles respond best to additive treatment. The most promising application of chemical treatment and additives appears to be on soils exhibiting only modest frost susceptibility. Dispersants are effective, but their permanence and durability are uncertain. Calcium chloride has been used for preventing frost heave in highway subgrade soils[112] and for improving compaction[34] results (see Section 5); its principal effect is a lowering of the freezing temperature of the soil water. Lignin and chrome lignin (see Section 11) have been successful in reducing ice segregation. The liquor changes capillary properties of soil and prevents soil water from migrating to form ice lenses. Sodium sulfate has been recommended as effective against heave in cemented soil.[117] Other additives have been used but generally at considerable expense.

Seasonal Scheduling

A practical way of achieving successful landfilling in a severely cold climate is by careful scheduling, e.g., by reserving more sheltered areas for winter operations and protecting soil borrow sources (see Unfrozen Soil Supply). In areas containing a variety of soils, gravels may be expected to freeze early and thaw early, whereas fine soils freeze late and thaw late; accordingly, a preference may develop for changing cover soil type during progression of the cold season.

Another scheduling option is to construct dikes and side retaining slopes requiring large volumes of soil during the summer and fall and to handle only waste and thin cover during the freezing season. It may even be reasonable to dispense with cover requirements during severely cold spells when the frozen water content helps keep the waste firmly in place and relatively free of pollution potential.

Trench Method

Not only does the trench method facilitate cold climate operations by providing a measure of shelter from the weather, but it also tends to protect the cover soil that remains partly buried until needed.

Snow Removal

It may be feasible at least locally to remove snow during slack periods of operation. Removing snow from flats reduces the amount possibly becoming available for infiltration upon thawing. Generally, try to avoid incorporating snow on daily cover into the next higher waste cell.

Snow Fences

Snow fences can provide some control on where drifting snow is deposited and thus may reduce the amount of snow that needs to be removed from the cover later.

Rapid Covering

Where percolation into waste cells is of particular concern, it may be advisable to incorporate in the operations plan contingency instructions for quick coverage before or during heavy snowfall. Coverage at this time might ordinarily be relaxed because of severe working conditions. However, covering may be most effective then, since snow falling on uncovered irregular, open waste surfaces may not be removable later before it melts and infiltrates (see Snow Interference).

Gas Vents

Gas vents and channels can be blocked detrimentally by icing, and the designer should evaluate depth of freezing in this context.

SECTION 17

MINIMIZATION OF FIRE HAZARD

The burning of waste is prohibited at sanitary landfills and industrial disposal sites. This restriction does not assure, however, that a fire will not be accidently ignited during operations, to smolder and break out, perhaps even after covering.

CONDITIONS FOR FIRE HAZARD

The most likely and direct cause of fire is in the unsuspected introduction of previously smoldering waste brought in trucks from the waste collection route. Possibilities for exothermic chemical reactions in some decomposing waste produce conditions favorable for supporting combustion, also. It is, therefore, essential that a fire potential is recognized and that suitable measures for preventing initiation and spread are incorporated in design.

Two conditions are required for a fire hazard to exist or develop. There must be flammable material in the landfill and sufficiently free access of air for oxidation. Where air can leak through relatively coarse cover or along void-rich waste layers from cracks or other openings along the side, there may be sufficient oxygen to sustain the process.

Large accumulations of coal mine wastes are beyond the scope of this manual; however, they serve as a good example of fire hazard potential. The solid waste of interest in this case is fine-grained rock and raw coal wasted as slurries from the crushing and washing plants. A survey of refuse banks in 13 coal-producing states revealed 292 burning banks.[118]

DESIGNING AGAINST FIRE HAZARD

Only one of the conditions mentioned above is usually susceptible to manipulation and design. This is a limitation of the access of air to discourage combustion. It is assumed that the type of solid waste delivered to the site is not subject to manipulation, and this aspect is not considered further. The following methods may be used to restrict the necessary oxygen supply.

Rapid Covering

The covering of smoldering or burning waste with damp soil will often be adequate to smother the fire completely. In view of the rarity but urgency of the problem, a liberal thickness of cover is recommended.

Selection of Soil

Selecting a fine-grained soil for cover is an effective way of reducing fire hazard. As explained in Section 9, clayey soils hold water better than coarse soils that drain freely, and the degree of saturation is a dominant factor in impeding gas flow.

Peat and other organic soils (Figure 1) constitute a special group that should be avoided as cover because of a susceptibility to burning.

Removal and Backfilling

Occasionally, it may be advisably expeditious to remove smoldering waste and backfill with patches of clay or other soil of low k value. Caution should be exercised in this remedy to avoid an explosive intermixing of methane, air, and heat.

High Water Content

High water content w, near saturation, is temporarily effective in extinguishing an existing fire or for stabilizing a landfill susceptible to combustion. Maintaining high w in the cover soil will probably not be feasible in the long range, where regular additions of water will increase percolation.

Trench Method

An effective method of reducing the surface area for potential air leakage is to use the trench method of disposal. This method works best in clayey soils[3] where an effective barrier to gas movement is supplied by the sidewalls.

Valley Filling Method

In the area method of solid waste disposal, the use of valleys as sites for fill may have advantage in controlling fire hazard. In this way the flanks of the landfill are naturally sealed by the valley slopes.[29] Active and abandoned strip mine pits can provide the same geometrical advantage, if the boundaries do not open into highly permeable soil or rock.

Compaction

Despite the difficulty of achieving good compaction on a spongy base of solid waste, extra compaction should be specified for cover over potentially combustible materials (see Section 9).

Cell Construction

Cell construction, a standard procedure for disposal of solid and hazardous waste, is thought to be effective in confining internal fires. The daily soil cover, which in a multiple-lift landfill constitutes the floor, sidewalls, and top of a cell, tends to contain any fire within the individual cell.

Separate Site

Wastes that are regarded as highly flammable should be excluded from the usual landfill and disposed in a separate area.[3] Special cover materials and procedures can be used there.

SECTION 18

CRACK RESISTANCE

To be effective in containing gases and excluding surface water, a cover soil should resist cracking. Otherwise, certain design features or construction procedures may be needed.

PHENOMENON OF CRACKING AT LANDFILLS

Detrimental effects of cracking in cover involve uncontrolled leakage of gas upward or percolate downward and easy access for burrowing animals and vectors. Cracks are ideal places for animals to enter in search of food and warmth in the waste below. By nature, cracks are well distributed and closely spaced in a drying soil layer, and correction is difficult, short of a complete renovation of the cover involving soil additions and recompaction. This is not to say that a crack-prone soil cannot be used as a daily cover. The process of cracking involves shrinkage upon loss of water by evaporation. Therefore, the relatively short exposure of a daily cover may not allow serious cracks to develop before the addition of more waste. The final cover deserves the most concern.

The phenomenon of crack formation is closely related to the clay mineralogy of the soil. Certain clay minerals are much more prone to shrinking and causing cracks. Montmorillonite clay is the most notorious, and soil engineers in vast areas of the central United States, particularly the Great Plains and Gulf states, face problems with these clay soils continually in road construction and building foundations (Figure 99). Likewise, operators of solid waste sites should be alert to potential problems locally.

Expansive behavior is at the opposite extreme of the spectrum of volume change phenomena from cracking, i.e., clay-rich soils may be prone to major problems of expansion when subjected to additions of water, then cracking upon drying. A common construction procedure, therefore, is to preserve the water content as close to natural content as possible.

The problem of volume changes in cover soils at landfills is considerably simpler than similar problems faced in highways and building foundations where most of the soil is in an undisturbed condition. Guidance provided below applies only to expansive soils in a remolded condition.

Fills containing appreciable percentages of expansive clay are sensitive to treatment during placement. It has been found that compaction density is sometimes critical, and expansive soil may undergo greater expansion if it is

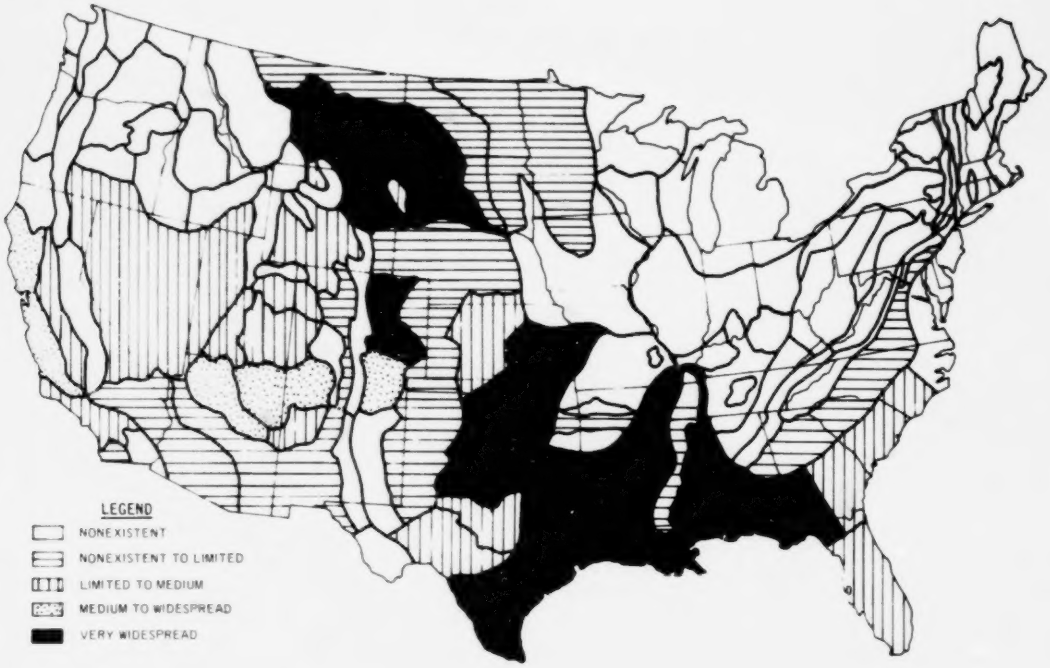


Figure 99. Estimated occurrence of expansive soils by physiographic unit (from Witczak).[119]

compacted to a higher density. This characteristic follows from the fact that there are more clay particles per unit volume in the dense condition. For a loosely compacted expansive soil, some of the expansion upon wetting effectively reduces the high porosity. Actually, this effect is less critical in landfill cover soil, since the concern is not so much for the expansion that takes place during wetting as for the shrinkage and cracking that takes place during drying. Therefore, high compactive effort should be beneficial since the densification might retard the loss of water, which leads to cracking.

INDICES OF EXPANSIVE BEHAVIOR

Methods of classifying expansiveness with convenient indices, such as Atterberg limits, have been developed in the last 30 years.[120,121] One of the most frequently cited[120] considers the colloid content, PI, and SL.

Another useful index is the clay content and specifically the particular clay mineral. Montmorillonite clays swell notoriously when the water content is increased. This behavior depends on the particular cation at specific positions in the crystal structure. Sodium montmorillonite (Wyoming bentonite) is the most expansive of all and can hold great volumes of water within its expanded crystal structure. Illite and kaolinite have limited or insignificant expansive behavior except in cases where the illite crystal structure has degraded to a mixed-layer condition of illite alternating with other clay minerals, such as chlorite or montomorillonite. This simplified explanation is intended only to emphasize that mineralogical analysis of a possible clayey cover can be useful in predicting the tendency for cracking.

The indexing summaries presented here (Tables 35 and 36) have resulted from extensive experience[15,120] with expansive clays, mostly in the Great Plains and Rocky Mountain regions. Swelling potential was measured as expansion at dead-load stresses of about 1000 psf. Indices found to be useful for predicting expansive (and cracking) behavior were the LL and the weight percent passing the No. 200 sieve (Table 35). The same source[15] has provided the correlation between PI and swelling potential shown in Figure 100.

TABLE 35. RELATIVE VOLUME CHANGE AS INDICATED BY PI AND OTHER PARAMETERS

Likelihood of Volume Change with Changes in Moisture	Plasticity Index		Shrinkage Limit
	Arid Regions	Humid Regions	
Little	0 - 15	0 - 30	12 or more
Little to moderate	15 - 30	30 - 50	10 - 12
Moderate to severe	30 or more	50 or more	10 and less

TABLE 36. VOLUME CHANGE AS INDICATED BY LL AND GRAIN SIZE

Passing No. 200 Sieve, percent	Liquid Limit percent	Probable Expansion percent
> 95	> 60	> 10
60 - 95	40 - 60	3 - 10
30 - 60	30 - 40	1 - 5
< 30	< 30	< 1

DESIGNING AGAINST COVER CRACKING

The following methods of design and operation are recommended to alleviate or avoid entirely the cracking problem.

Selection of Soil

Criteria based on LL and PI should be used to choose a soil with low-cracking potential (Tables 35 and 36).

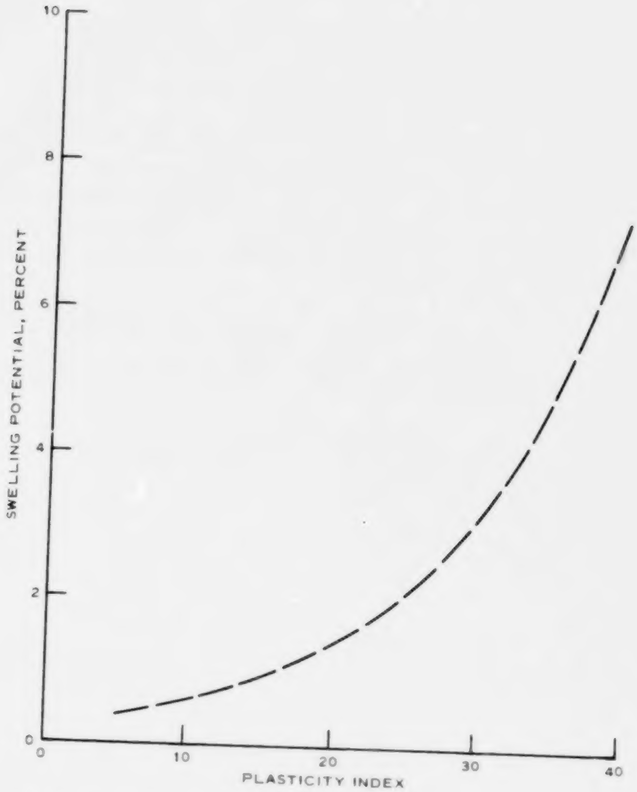


Figure 100. Plasticity index as related to swelling potential at 1-psi surcharge.

Moisture Preservation

High moisture within the cover soil may be maintained by frequent sprinkling to compensate for water loss by evaporation. There is a self-healing mechanism working to advantage. Sprinkled water or natural precipitation may migrate preferentially along the developing cracks but will quickly cause expansion of the crack walls with resultant crack closing.

Compaction

Compaction is probably always a beneficial procedure. Any detrimental expansive behavior at the surface is probably negligible compared with the benefits in reduced permeability and impeded drying. Compaction on the dry side of optimum water content should be at least temporarily beneficial since the tendency is for water to be imbibed and the clay to swell.[19] This action works against the cracking behavior.

Layered System

A layered cover system may solve the cracking problem by sufficiently reducing evaporation from the clay layer. Such a system should consist of a compacted clay layer with a layer of free draining sandy soil above to impede evaporation. The surcharging effect of the upper layer on the clay will also help suppress expansion and subsequent cracking.

Increased Cover Thickness

Increasing the thickness of cover insulates buried portions from the heat of the sun and reduces evaporation and cracking. Thickening that is undertaken to remedy a developing problem of cracking should be preceded by sprinkling, sufficient to expand the soil and close cracks.

Lime Treatment

The usual additive for reducing swell is lime; therefore, it is recommended for use on troublesome clay soil covers. Preferably work the lime in mechanically for best results. See Section 5 for additional explanation.

SECTION 19

ESTABLISHMENT AND SUPPORT OF VEGETATION

Sound, vigorous vegetation on soil cover over solid waste is highly cost-effective.[122] Primary benefits are often identified as decreases in erosion by wind and water (see Sections 10 and 11). Vegetation reduces raindrop impact and runoff velocity and strengthens the soil mass with root and leaf fibers. At the same time, however, the soil's infiltration capacity is increased so that considerable water enters. The increased infiltration is offset at least partly by transpiration from vegetation, but the relative importance of these offsetting processes is a complicated question that has not been conclusively answered.[123-125] See Section 8 for discussion of the important effects of vegetation upon infiltration and percolation.

CONSIDERATIONS UNIQUE TO LANDFILLS

Rapid establishment and maintenance of perennial vegetation or self-reseeding annual vegetation can be accomplished on soil covering solid waste only by carefully addressing soil type, nutrient and pH levels, climate, species selection, mulching, and seeding time.[126] Fertile soils, if available at all for landfill cover, are usually cost-prohibitive, so that nonproductive soils or subsoils often have to be used. Landfill cover is also usually shallow.

These shortcomings of the soil cover are compounded where the cover has been designed to impede percolation. A clay or plastic barrier makes the plant-root zone susceptible to swamping after rains since no vertical drainage occurs. Upon saturation, the soil becomes anaerobic, a condition which, depending upon the duration, may kill progressively larger roots. Short periods of swamping weaken the vegetation; longer periods may cause a complete loss.

At the other extreme, thin cover soil dries excessively during dry periods. No deep-soil moisture is available to tide the plants over even moderate droughts. Plants that have been weakened by prior waterlogging or that are not drought-tolerant are especially vulnerable. Irrigation may be necessary during prolonged dry spells to prevent complete loss of plant cover.

Landfills may continue to produce gases and soluble organic decomposition products for years after closure, and vegetation can be damaged.[127,128] Fine-grained soil cover over decomposing waste helps shield shallow plant roots from gases and leachate. On the other hand, shrubs and trees may penetrate the cover with long roots and cause leaks of water into and gases from the landfill. Inspection of damaged vegetation on landfills can help identify vulnerabilities and disadvantages of plant species, since no systematic study has yet been undertaken.

SOIL FACTORS

Major factors determining effectiveness of the soil for supporting vegetation are grain size, pH level, and nutrient content. Laboratories capable of evaluating soil for these factors are located throughout the United States and most county agents can provide guidance. Sampling should be representative of all soils (depths and areas) to be used since the cover will usually consist of a mixture. Table 37 indicates typical ranges of organic matter and nutrients in soils for various levels of plant vitality.

Grain Size

Two common soil classification systems are described in Section 1, and a rating of soil types (based on grain size) for the support of vegetation is given in Table 6. In the USDA system, a soil composed of a mixture of clay, silt, and sand such that none of the components dominate is called a loam. The stickiness of the clay and the floury nature of the silt are balanced by the nonsticky and gritty characteristics contributed by sand component. A loam is rated overall best soil type as it is easily kept in good physical condition and is conducive to good seed germination and easy penetration by roots.

Clay-rich soils may be productive when in good physical condition, but they require special management methods to prevent puddling or breaking down of the clay granules. Silt-rich soils lack the cohesive properties of clay and the grittiness of sand, are water retentive, and usually are easily kept in good condition. Soils made up largely of sand can be productive if

TABLE 37. RELATIVE LEVELS OF ORGANIC MATTER AND MAJOR NUTRIENTS IN SOILS[126]

	Organic Matter, percent					
Relative Level*	Sand, Loamy Sand	Sandy Loam, Loam, Silt Loam	Clay Loam, Sandy Clay, Clay	Nitrogen lb/acre	Phosphorus lb/acre	Potassium lb/acre
Very low	<0.6	<1.6	<2.6	<20	<6	<60
Low	0.6-1.5	1.6-3.0	2.6-4.5	20-50	6-10	60-90
Medium	1.6-2.5	3.1-4.5	4.6-6.5	50-85	11-20	91-220
High	2.6-3.5	4.6-5.5	6.6-7.5	85-125	21-30	221-260
Very high	>3.5	>5.5	>7.5	>125	>30	>260

* Medium level is typical of agricultural loam soil. Low levels need supplemental fertilization; high levels need no fertilization under normal circumstances.

sufficient organic matter is present internally or as a surface mulch to hold nutrients and moisture; sandy soils tend to dry out very rapidly and lose nutrients by leaching.

The general classification of a soil can usually be estimated by visual inspection; however, soil typing by an appropriate soil testing laboratory is preferred. Rather minor differences in soil type can influence selection of species or mulch.

pH Level

Soil used to cover solid waste is usually composed of a mixture of soil and subsoil, in some cases from more than one locality. The pH of the soil is an important factor to be considered. The amount of lime necessary to neutralize a given soil depends upon soil pore water pH and reserve acidity. The reserve acidity, or buffering capacity, is a single factor that incorporates several variables; soils with high levels of organic matter and/or clay require higher amounts of lime for pH adjustment. The usual way of characterizing the buffering capacity is as tons/acre of lime necessary to adjust the soil pH to about 6.5.

The pH of the subsoil (where appreciable in the cover) may be particularly critical to lime requirements. Acidic subsoils need larger amounts and repetitive applications of lime. Buried landfill wastes may act much like acid subsoils, so that large lime applications or frequent liming intervals may be necessary.

If the soil pH is greater than about 8, the solubilities of phosphorus, iron, zinc, and manganese are so low that the plant cannot take up these nutrients even though they are present in sufficient quantities. If the soil pH is below 5, the concentrations of soluble manganese and aluminum often are high enough to be toxic and the availability of molybdenum and phosphorus is limiting.

Nitrogen and Organic Matter

Nitrogen is of special importance in establishing vegetation, because it is needed in relatively large amounts (Table 37) during vigorous growth, is easily lost from the soil, and is the most expensive nutrient to supply. All but a small part of soil nitrogen exists in organic forms, both in decaying plant material and in the microorganism decomposing the organic matter. Measurements of the nitrogen content of soil and its organic content are intimately related. Nitrogen accumulates in soil microorganisms where it is used over and over again as old cells die and new ones are formed. The nitrogen contained in the microbial cells is unavailable for use of plants growing on the soil until the organisms die. The rate at which nitrogen is released by organic matter breakdown depends upon the moisture and temperature conditions in the soil. High or low moisture retards release; high temperature and moderate moisture levels produce maximum release rates. Most landfill cover soils consist largely of subsoils or mixtures of subsoil and topsoil, so that they can be assumed to be low in organic matter content. The most cost-effective method of adding organic matter is by mulching with straw cellulose, etc. Once vegetation becomes established, the plants themselves will add organic matter.

The amount of nitrogen fertilizer required by a given soil depends upon the amount of organic matter present (higher organic matter levels requiring higher application rates), the soil texture (more is required on sandy soils), the seed mixture chosen (more is required for grasses than legumes), the criticalness of the area (potential for erosion damage), and economic factors (nitrogen fertilizer is the most expensive). Generally 50 to 85 lb/acre of nitrogen are recommended (Table 37) for landfill cover seeded with grass. Fertilizers are rated by the amount of nitrogen they contain per weight of fertilizer (e.g., 6 percent nitrogen). To calculate the required amount of fertilizer, simply divide the recommended nitrogen application by the fractional amount of nitrogen in the fertilizer. For example, to apply 50 lb/acre of nitrogen using fertilizer that is 6 percent nitrogen, simply divide 50 by 0.06 to get 833 lb/acre of fertilizer.

Phosphorus

Much less phosphorus than nitrogen is held in the organic portion of the soil. Results of phosphorus tests are usually expressed as pounds of readily extracted phosphorus per acre-furrow slice (6-in. depth). Representative levels are shown in Table 37. Unlike nitrogen, phosphorus is not mobile in the soil and thus is lost very slowly to leaching. One application of phosphorus usually will last several growing seasons.

Phosphorus content is expressed either as percent phosphorus pentoxide (P_2O_5) or, as is now the trend in industry, percent elemental phosphorus. Care should be taken regarding the basis of characterization since percent P_2O_5 is 2.3 times an equivalent percent phosphorus. Generally, at least 15 lb/acre of phosphorus is recommended as a starter. The availability of phosphorus to the plant is quite dependent on pH. At optimum pH values (6.2-6.8), amounts of 50 lb/acre are usually adequate; at pH values below 6.2 or between 6.9 and 7.5, about 80 lb/acre are needed for optimum growth. Under very alkaline conditions (pH greater than 7.5), phosphorus levels of 110 lb/acre are required. These recommendations are for raw subsoils or for sandy or high clay soils of low organic material content.

Potassium

The potassium soil tests are generally based upon pounds of exchangeable K per acre. Fertilizer analyses are often provided in terms of percent K_2O, which is greater than an equivalent percent potassium by a factor 1.2. The industry is now changing over to the elemental potassium basis, and care must be taken in calculations.

Potassium is much less important in grass establishment than in legume establishment and maintenance; thus, the rate of application depends upon both test results and species to be seeded. A minimum application of 26 lb/acre of potassium (32 lb/acre K_2O) as a starter is recommended under any circumstances. Applications can run as high as 230 lb/acre of potassium (277 lb/acre K_2O) on impoverished soils where legumes are to be seeded.

Potassium is moderately mobile in the soil and is slowly leached out, but one heavy application should be adequate for several growing seasons.

Other Nutrients and Toxic Materials

Other mineral nutrients needed in small amounts by all plants for adequate growth are usually present in most soils, or as impurities in typical fertilizers, and thus are not determined in typical soil tests. Deficiencies rarely limit plant growth and should be suspected only under unusual circumstances.

Soils with toxic levels of heavy metals or with high levels of salts present special problems, and their use as final cover material should be avoided unless no other soils are available. If these soils must be used, selection of tolerant plant species is usually the most effective way to overcome the associated problems. In general, soils that support an adequate or reasonable level of vegetation in their native state will not present toxicity problems when used for landfill cover.

CHOICE OF VEGETATION

General guidance in selection of plants and time of seeding is provided below. More specific supplemental data may be available from county agents or seed companies.

Species Selection

Each species of grass, legume, shrub, or tree has its climatic, physiographic, and biological strengths and limitations. Moisture, light, temperature, elevation, aspect, balance and level of nutrients, and competitive cohabitants are all parameters that favor or restrict plant species. The selection of the best plant species[129] for a particular site depends upon knowledge of plants that have the desired characteristics. Table 38 gives the major parameters usually important to species selection and examples of grasses and legumes exhibiting these parameters. Particularly important characteristics are low growing and spreading from rhizomes or stolons; rapid germination and development; and resistance to fire, insects, and disease. Plants that are poisonous or are likely to spread and become noxious should be avoided.

A very large number of species of grasses and legumes are available for reclamation use. Species that find wide and frequent application are described in Tables 39 and 40. A local agronomist should be consulted for recommendation of locally adapted or newly introduced plant varieties.

Time of Seeding

Probably the most critical of all decisions in the successful establishment of vegetative cover on poor soils is the time of seeding. The optimum time of seeding depends on the species selected and the local climate. Tables 39 and 40 recommend times for certain grasses and legumes based on local conditions.

TABLE 38. IMPORTANT CHARACTERISTICS OF GRASSES AND LEGUMES*

Characteristic	Degree	Common Examples
Texture	Fine	Kentucky bluegrass, bentgrass, red fescue
	Coarse	Smooth bromegrass, reed canarygrass, timothy
Growth height	Short	Kentucky bluegrass, buffalograss, red fescue
	Medium	Redtop, perennial ryegrass
	Tall	Smooth bromegrass, timothy, switchgrass
Growth habit	Bunch	Timothy, big bluestem, sand dropseed, perennial ryegrass
	Sod former	Quackgrass, smooth bromegrass, Kentucky bluegrass, switch grass
Reproduction	Seed	Red and alsike clover, sand dropseed, rye, perennial ryegrass, field bromegrass
	Vegetative	Prairie cordgrass, some bentgrasses
	Seed and vegetative	White clover, crownvetch, quackgrass, Kentucky bluegrass, smooth bromegrass
Annual	Summer	Rabbit clover, oats, soybeans, corn, sorghum
	Winter	Rye, hairy vetch, field bromegrass
Perennials	Short-lived	Timothy, perennial ryegrass, red and white clover
	Long-lived	Birdsfoot trefoil, crownvetch, Kentucky bluegrass, smooth bromegrass
Maintenance	Difficult	Tall fescue, reed canarygrass, timothy, alfalfa
	Moderate	Kentucky bluegrass, smooth bromegrass
	Easy	Crownvetch, white clover, birdsfoot trefoil, big bluestem
Shallow rooted	Weak	Sand dropseed, crabgrass, foxtail, white clover
	Strong	Timothy, Kentucky bluegrass
Deep rooted	Weak	Many weeds
	Strong	Big bluestem, switchgrass, alfalfa, reed canarygrass
Moisture	Dry	Sheep fescue, sand dropseed, smooth bromegrass
	Moderate	Crested wheatgrass, red clover
	Wet	Reed canarygrass, bentgrass
Temperature	Hot	Lehman lovegrass, fourwing saltbush, ryegrass
	Moderate	Orchard grass, Kentucky bluegrass, white clover
	Cold	Alfalfa, hairy vetch, smooth bromegrass, slender wheatgrass

* Adapted from Reference 130.

TABLE 39. GRASSES COMMONLY USED FOR REVEGETATION*

Variety	Best Seeding Time	Seed Density† seeds/ft^2	Important Characteristics	Areas/Conditions of Adaptation
Redtop bentgrass	Fall	14	Strong, rhizomatous roots, perennial	Wet, acid soils, warm season
Smooth bromegrass	Spring	2.9	Long-lived perennial	Damp, cool summers, drought resistant
Field bromegrass	Spring	6.4	Annual, fibrous roots, winter rapid growth	Cornbelt eastward
Kentucky bluegrass	Fall	50	Alkaline soils, rapid grower, perennial	North, humid, U.S. south to Tennessee
Tall fescue	Fall	5.5	Slow to establish, long-lived perennial, good seeder	Widely adapted, damp soils
Meadow fescue	Fall	5.3	Smaller than tall, susceptible to leaf rust	Cool to warm regions, widely adapted
Orchard grass	Spring	12	More heat tolerant but less cold resistant than smooth bromegrass or Kentucky bluegrass	Temperate U.S.
Annual ryegrass	Fall	5.6	Not winter hardy, poor dry land grass	Moist southern U.S.
Timothy	Fall	30	Shallow roots, bunch grass	Northern U.S., cool, humid areas
Reed canarygrass	Late summer	13	Tall coarse, sod former, perennial, resists flooding and drought	Northern U.S., wet, cool areas

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* Taken from many sources, but especially 126 and 129.

† Number of seeds per square foot when applied at 1 lb/acre.

TABLE 40. LEGUMES COMMONLY USED FOR REVEGETATION*

Variety	Best Seeding Time	Seed Density† seeds/ft^2	Important Characteristics	Areas/Conditions of Adaptation
Alfalfa (many varieties)	Late summer	5.2	Good on alkaline loam, requires good management	Widely adapted
Birdsfoot trefoil	Spring	9.6	Good on infertile soils, tolerant to acid soils	Moist, temperate U.S.
Sweet clover	Spring	6.0	Good pioneer on non-acid soils	Widely adapted
Red clover	Early spring	6.3	Not drought resistant, tolerant to acid soils	Cool, moist areas
Alsike clover	Early spring	16	Similar to red clover	Cool, moist areas
Korean lespedeza	Early spring	5.2	Annual, widely adapted	Southern, U.S.
Sericea lespedeza	Early spring	8.0	Perennial, tall erect plant, widely adapted	Southern, U.S.
Hairy vetch	Fall	0.5	Winter annual, survives below 0°F, widely adapted	All of U.S.
White clover	Early fall	18	World-wide, many varieties, does well on moist, acid soils	All of U.S.
Crownvetch	Early fall	2.7	Perennial, creeping stems and rhizomes, acid tolerant	Northern U.S.

* Taken from many sources but mainly 126 and 129.

† Number of seeds per square foot when applied at 1 lb/acre.

Most perennials require a period of cool, moist weather to become established to the extent that they can withstand a cold winter freeze or hot summer drought. For most species in most localities, early fall seeding (late August in the north through early October in the south) allows enough time for the plants to develop to the stage that they can withstand a hard winter. Plants then have a good start for early spring growth and can reach full development before any hot summer drought. Early fall planting makes germination and early growth possible in warm weather, the weather growing cooler as the plants develop. Spring planting is usually second choice for all but a few of the more rapidly developing perennials. Germination and early development are slowed due to the cool early spring weather. Late frosts often severely damage the young plants. Late spring planting does not allow enough time for most perennials to mature before summer, and annual weeds will usually out-compete the preferred perennial species.

Annuals generally are best seeded in spring and early summer. They complete their growth quickly before the summer heat arrives and the soil moisture is depleted. Thus, in late spring and in summer, the annuals easily out-compete the perennials. Annuals can, however, be planted for quick vegetative cover any time the soil is damp and warm.

SEED AND SURFACE PREPARATION

Bare soil as a seeding medium suffers from large temperature and moisture fluctuations and from rapid degeneration due to wind and water erosion.

Mulch in General

Mulches make the establishment of suitable plant cover more efficient by reducing evaporation, moderating soil temperatures, preventing crusting, increasing rain infiltration, and controlling wind and water erosion. Mulches also help to overcome deficiencies in organic matter typically found in landfill cover soils. Almost any material spread, formed, or simply left on the soil surface will act as a mulch. A wide variety of materials are used commonly or under special circumstances: straw and other crop residues, sawdust, wood chips, wood fiber, bark, manure, brush, jute or burlap, gravel, stones, peat, paper, leaves, plastic film, and various organic and inorganic liquids.

The effectiveness of any mulch depends upon many factors including the physical and chemical properties of the soil, the land-forming or cultural practices, species to be seeded, and the characteristics of the mulch itself, such as its color, roughness, and manner of application. The effect of color and roughness are directly related to the radiation balance at the soil surface and, consequently, the heat transfer into and out of the soil. Slope, aspect, and orientation of the soil surface also influence the solar energy input. Other factors determining mulch efficacy are steepness and length of slope, soil texture and depth, rate of application of mulch, and the weather before, during, and after mulch application. Selection depends upon characteristics of the area to be stabilized and the availability, cost, and properties of the mulch material. Several of the more common and effective mulches and their applications are described below.

Crop Residues

Crop residues, such as straw and hay, are readily available and are widely used mulches; and of these, straw is by far the most common mulch in all parts of the United States. Straw's long and fibrous texture is excellent for erosion control, and its low nutrient value retards rotting so that it normally lasts a full season. Straw reflects much sunlight and thus may have the disadvantage of keeping the soil cool early in the spring or late in the fall, when warmth would facilitate germination and early growth.

Where erosion is not a problem, an application of 1.5 tons/acre is recommended. On higher slopes or where erosion is expected to be a problem, 2 tons/acre produces better results. Application rates over 2.5 tons/acre often result in reduced germination and emergence, and such high rates should be avoided. Beater-type mulch spreaders work well on level areas, but a blower type is better for steep slopes. Baled material tends to fall in bunches unless cut or shredded and scattered or blown. Wheat straw is generally preferred over oat straw since oat straw decays more rapidly and usually contains seeds that compete with the perennials for space and water. Hay, in comparison to straw, is difficult to spread, and it decomposes rapidly. However, hay possesses some nutritive value and reflects less solar radiation. Overall, however, the best plant residue mulch is the one most available and nearest.

Straw should be anchored, if possible, so that it does not blow or wash, making piles and leaving bare spots. A disk harrow (with disks set straight) that is run over the mulch across the slope is effective at anchoring. Notched disks work best. Running over the mulch with a special punch roller or a cultipacker also helps to anchor the mulch. Even running over the spread straw with a bulldozer helps keep the straw in place. Asphalt or resins can be used as a binder or to anchor, but while they greatly increase effectiveness, they also increase cost.

Crop residues produced in place can be effective in special circumstances. Rapidly growing crops are especially useful as temporary cover when placed in late spring or early summer, since chances of successfully seeding perennial grass-legume then are low. Subsequently, the summer annual crop acts as a natural mulch for fall or spring seeding of the permanent seed mixture. Rapid-growing, coarse grasses, such as Sudan grass or a local equivalent, are good choices as they are widely adaptable and the tall stiff stalks are effective as a mulch. One disadvantage of the summer cover crop regime is that the crop depletes available soil moisture in dry areas, causing the seeding of perennials to fail. On the other hand, in wet areas, the soil under the cover crop dries very slowly and often remains too wet to fertilize and work into a good seed bed even into the next spring.

Wood Residues and Paper

Wood residues, such as sawdust, wood chips, bark, and shavings, are used extensively in many areas. Wood residues are a concentrated source of organic matter, and supplementary nitrogen should be applied with the mulch. Advantages of wood residues are that they are easy to apply, long lasting, and less susceptible to blowing and fire than crop residues. Disadvantages include their competition for available nitrogen, their lowering of the pH, and the frequent packing of the finer materials. Chips, shavings, and millrun sawdust make good mulch, but the finer resaw sawdust packs tightly and may retard aeration and infiltration. Microorganisms carrying on decomposition of the highly cellulosic mulches (most are less than 0.2 percent nitrogen) compete with plant roots for available nitrogen.

Wood cellulose fiber and shredded paper are available commercially for use in several designs of hydroseeders and/or hydromulchers. The products are furnished in bales that are mixed with water to form a sticky paste and sprayed directly in place with specialized equipment. The dried slurry sticks together and forms an effective mulch at much lower application rates than required of nonslurried materials. Usually, seed and fertilizer are mixed directly into the same slurry so that seeding, fertilizing, and mulching are accomplished in a single operation. The low labor requirement and speed of hydroseeding makes it the method of choice in many, large-area projects.

Bituminous Products

Petroleum-based products, such as asphalt and resins, are often suitable and are frequently used as mulching materials. Specially formulated emulsions of asphalt under various trade names have been used throughout the world to prevent erosion, reduce evaporation, promote seed germination, and warm the soil to advance the seeding date. The film clings to but does not penetrate deeply into the soil; it is not readily destroyed by wind and rain and remains effective from 4 to 10 weeks. Application rates of 1000-1200 gal/acre are usually required to control erosion. Asphalt mulches cost about twice the applied cost of a straw mulch.

Asphalt emulsions are often used in conjunction with straw mulches to increase resistance to wind and water damage. Application rates are low so that the straw is merely cemented together without complete coverage by the asphalt.

Resin-in-water emulsions are often as effective as well-anchored straw as mulching materials. Resin emulsions are stable and can be diluted with large amounts of water without breaking the emulsion. The resins resist weathering by wind, rain, or soil bacteria and leave the soil surface permeable to water. Resin is usually applied at a rate of 600-800 gal/acre, and costs are equivalent to the asphalt emulsion.

Black asphalt absorbs solar energy and greatly increases the warming of soils at all times of the year. Germination and development are greatly accelerated in late fall and early spring, but in summer, the absorbed heat can be lethal to young seedlings. Aluminized asphalt and white-pigmented resins have been developed to overcome these problems but have not found wide application.

Plastic Films

Plastic films are sometimes effectively used on very steep slopes or under high-erosion conditions. The film is expensive, difficult to put down, and very susceptible to wind damage. Seedling emergence must be monitored closely, and the film ventilated or removed at the right time. Even 1 or 2 days of temperatures over 80°F is enough to kill most seedings. Often when the film must be removed, the seedling cover is not nearly complete and serious erosion results.

Other Techniques

Other techniques can be useful under special circumstances or availability. Gravel and crushed rock have the advantage since they are permanent. A 1- to 2-in. layer of gravel will control surface erosion and vegetation development in the driest of areas. Gravel with a minimum diameter of 1/2 in. will resist winds to 85 mph.

Manure is an excellent mulch, which can often be found at local feed lots. Manure acts as both a mulch and a slow-release fertilizer of fair quality but is not reliable in erosion control as it tends to decompose rapidly and is hard to spread evenly. Jute netting and woven thread-and-paper fabric are available commercially for stabilizing very steep or critical areas. These products are especially effective when used in conjunction with a straw or hay under-mulch; however, both are expensive and difficult to put down, requiring insertion of several thousand wire staples per acre to anchor them.

Wattling is another technique[131] that may be used to help establish vegetation on vulnerable slopes. Tied bundles of flexible twigs are laid in furrows or trenches along contours, staked down, and partially covered with soil. Rows of wattles act to trap soil moving down the slope, to dissipate energy of soil and water movement, and to reduce effectively the slope of small areas immediately upslope. The areas between wattle rows are thus made favorable for establishment of vegetation. If the wattle is made of twigs that take root easily, such as willow, the wattle itself becomes a part of the semipermanent or permanent stabilization system.

MAINTENANCE OF VEGETATION

Once the selected vegetation is established on the landfill, at least a minimum amount of maintenance is necessary to keep less desirable, native species from taking over and weak areas in the cover from developing. In most areas judicious, twice yearly mowing will keep down weed and brush species. Annual fertilization (and liming if necessary) will generally allow desirable species to out-compete the lower quality weedy species. Occasional use of selective herbicides usually controls noxious invaders, but care must be taken to avoid injuring or weakening the desirable species, lest more harm than benefit results in the long run. In rare circumstances, large insect populations may threaten the stand of vegetation so that insecticide application becomes desirable.

DESIGNING FOR VEGETATION

The role of vegetation over solid waste is to protect, as quickly as possible, the exposed final cover soil against erosion and disruption. Therefore, it is vitally important that the soil support and hold healthy vegetation. The following recommendations are set forth on the basis of discussions in this and previous sections.

Topsoil

A preliminary step in establishing vegetation is to stockpile and then reuse the original topsoil. The less fertile underlying soil will be available as daily or intermediate cover. As the operation nears completion, the stockpiled topsoil can be used in the final cover to facilitate rapid growth of grasses and/or shrubbery. The original topsoil must be significantly more fertile than underlying soil strata; otherwise, stockpiling is not practical or economical.

Suitable Seed Mix

Regional vegetation should be considered for planting at the disposal site. This continuity with existing vegetation is important from the aesthetic point of view. Consideration should also be given to future use of the site.. For example, if a golf course is planned for construction on a municipal waste disposal area, appropriate species of trees and grasses should be selected and planted toward the close of disposal operations. Tables 39 and 40 recommend numerous grasses and legumes for consideration.

Swamping or Droughty Conditions

Where swamping or droughty conditions are anticipated because of climate, cover configuration, or soil type, special consideration should be given to swamping-tolerant or drought-resistant vegetation.

Maximum Slopes

A general rule of thumb[132] provides that 1V on 2H is the maximum slope on which vegetation can be established and maintained, assuming ideal soil with low erodibility and adequate moisture-holding capacity. In soils less than ideal, maximum vegetative stability cannot be attained on slopes steeper than about 1V on 3H. Optimum vegetative stability generally requires slopes of 1V on 4H or flatter.

Conditioning and Fertilizing

Where soil is deficient, fertilize to reach adequate levels of nutrients and pH. Guidance is provided under SOIL FACTORS. Flexibility for improving available cover soil may be found in carefully considering some inert wastes as additives. Fly ash has locally been mixed[29] with cover soil to provide good soil texture with enhanced water retention capacity. The alkalinity of fly ash may also provide an advantageous compliment to acid soils.

Mulching

Mulch application is a cost-effective method of erosion control. Mulch applied to both flat and steep slopes attenuates the energy transfer and splash action of raindrops. This attenuation minimizes water erosion until vegetation has a chance to establish a stable root system. Often a tacking material is applied to reinforce straw/hay mulch. Asphalt cements, chemical stabilizers, and netting are used for this purpose, but these materials may also be used alone as mulches.

Netting and Wattling

Freshly seeded cover may be protected with netting of jute, paper yarn, plastic netting, fiberglass scrim, and filter cloth. The netting is placed over the seeded soil, so that the vegetation penetrates as it grows. Areas of slow growth remain protected by the netting until vegetation is established. This technique is suitable for use in flat areas and on slopes. Also consider wattling on erosion-prone slopes.

Partitioning of Area

Partitioning of the disposal area may prove effective toward early achievement of stable vegetation growth. Accordingly, a relatively small part of the site can be filled, covered, seeded, and mulched in a short period of time before proceeding to the next. Exposure to erosion and other adversities is reduced to a minimum. With some overlap of closure of one subarea on the opening of another, the regular personnel and equipment on site may be used efficiently for vegetation preparation during disposal downtime.

Maintenance

Waste disposal areas have long lives, and permanent vegetative cover should be maintained. Once a cover of vegetation is started and a stable, extensive root system develops, organic matter and decomposition processes develop a layer of humus capable of perpetuating the cover vegetation. However, erosion forces, burrowing animals, etc., may damage parts of this cover of soil and vegetation. Provisions should be made for maintenance, specifically for transplanting grass sods, planting new seeds or shrubs, and replacing eroded soil during the inactive life of the area.

SECTION 20

ANIMAL AND VECTOR CONTROL

Soil covering municipal solid waste should function to minimize animal attraction and vector breeding. This requirement is normally not so important in land disposal of industrial and hazardous wastes because potential food and breeding conveniences are much less than in municipal wastes. This section suggests procedures and soils to minimize two basic animal nuisances, birds and burrowing animals.

MINIMIZING ATTRACTIVENESS TO BIRDS

Birds are attracted by the availability of food (and perhaps of warmth) and they have occasionally become a serious problem, e.g., near airports.[133] In order to reduce the attraction of large colonies, municipal waste should be covered quickly. The type of soil is not important as long as the cover:

a. Forms a thick layer over the waste.

b. Is strong enough to discourage digging by birds.

c. Is first placed early in the daily disposal operation.

DISCOURAGING BURROWING ANIMALS

When a disposal area is properly designed and constructed for primary functions, such as erosion control, burrowing animals will automatically be deterred. However, control of burrowing animals is occasionally a primary cover function, and related experiences are pertinent. In rolled earth dams,[134-136] animals create passageways for water to penetrate and damage the structural integrity. A similar damage can be expected in sanitary landfills where such holes may lead to increased water percolation.

Burrowing animals, such as rats, dig tunnels into municipal waste for shelter and waste food scraps. To make waste areas unattractive to burrowing animals, wastes should be covered daily with a soil that will not easily stand open to provide passageways. Since animal tunnels depend on the arching phenomenon to remain open, a soil possessing low arching potential should be used.

Arching is a process of ground stress transfer where overburden load is carried around a weak zone or opening by the mobilization of shearing strength. Use of a cover soil with low shear and tensile strengths should favor burrow instability and discourage burrowing animals. Generally, as percentages of silt-clay size particles are increased in mixtures (remolded) of sand, silt, and clay, strength increases. Accordingly, dry, loose, clean granular soils, such as sand and well-graded gravel, should be effective in deterring burrowing animals. When these soils are unavailable, mixtures of creosote and soil may serve as substitutes.[134,136]

MINIMIZING VECTOR ACCESS

Municipal waste generally attracts flies and mosquitoes that are capable of transmitting disease. Flies are attracted by the availability of food and breeding areas in the wastes, and mosquitoes by the water-filled containers that serve as hatcheries for eggs.

Soil cover should be added over municipal waste early in the daily disposal operations. A strong, dense, well-graded soil will impede vector larvae emergence. This type of soil includes gravel, sand, silt, and clay provided large voids are not developed. Clays and clay-rich soils are particularly effective provided they are not cracked. Where flexural cracks (Figure 26) tend to develop, a cohesionless soil may be best.

SECTION 21

AESTHETIC CONSIDERATIONS

Municipal/industrial waste disposal areas should be inoffensive and acceptable. The role of cover for aesthetics is simply:

a. To minimize blowing paper during daily operations.

b. To aid in the control of odors.

c. To reduce quickly the harsh appearance of exposed solid waste.

Any soil type should serve adequately. Attention to these considerations will help maintain good public relations in the vicinity of a waste disposal site. Aesthetics may not be primary functional requirements of cover soils but are interrelated with other requirements and should be kept in mind always during design/construction phases.

SECTION 22

FUTURE CONSTRUCTION AND LAND USE

This section is concerned with the measures that can be taken during design and construction to facilitate and improve future land use. Specifically, those aspects concerning the composition and configuration of the cover are emphasized. Efficient use of landfill after the primary waste disposal purpose has been achieved requires long-range planning. Planning is particularly important where construction of a building is anticipated. The consequences of changing plans for the landfill will usually require costly modifications, such as the removal of settlement-prone cover-waste layers.

DISPOSAL AREAS AS SITES FOR CONSTRUCTION

A conservative viewpoint has prevailed for many years in the state of the art of using landfills. The tendency is to think of landfills for use as parks and the like rather than to support structures. Actually, a spectrum of uses can be opened through proper planning. Thus, it may be possible to provide for light structure foundations by doubling or tripling the ratio of soil cover to waste material in the top lifts below the proposed foundation grade. Such increase in the proportion of soil would, of course, reduce the primary function of the landfill, i.e., to hold solid waste. The short-range and long-range objectives must be balanced in reaching a decision on such a design modification.

Supportive Characteristics of Waste

The conservative attitude about future construction on landfills centers around the poor supportive qualities of most solid waste. Table 3 shows an average composition of municipal refuse. The composition clearly indicates an inherent resistance to compaction and a latent ability to absorb water as it becomes available. Both characteristics tend to delay the sanitary landfill from the trend toward increasing stability with time expected in fills of soil or rock. Figure 101 confirms the severity of the problem but suggests that predictions of settlement may be adequate for engineering design. At the present time, little can be done by manipulation of cover soil composition and placement to counteract unfavorable characteristics. There is some leeway for manipulation of the configuration of the cover, however, as mentioned above.

Industrial sludges and slurries may have even poorer qualities, besides an enduring potential for serious pollution; they are however more uniform and predictable (see NATURE OF SOLID WASTE in Section 1). Some sludges by virtue of a colloidal nature can remain for years in a saturated condition with a

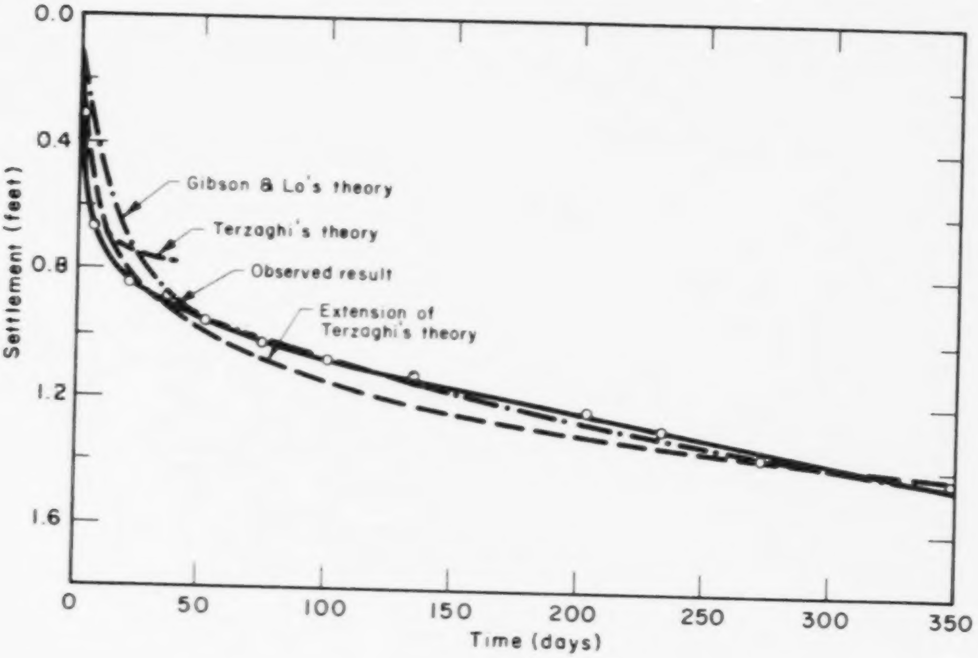

Figure 101. Settlements predicted and observed from loading 10-ft-thick section of old municipal landfill.[137]

very high water content. Relatively thin cover interstratified with such slimes, sludges, or slurries may do little to improve the condition as a foundation and, in fact, may actually cover up, obscure, and preserve substrata that are entirely unsuitable as foundation; however, see Section 15.

Use Options Available

Several potential uses for sanitary landfills and industrial waste sites involve little consideration of the integrity of the mass. These uses fall into the following general categories:

a. Nature park.

b. Recreation park.

c. Tree farm.

d. Wild area.

e. Animal refuge.

Landfill uses that will require some planning of cover soil composition and configuration include the following:

a. Paved parking area.

b. Tennis court, etc.

c. Vehicular track or strip.

d. Ski or toboggan hill.

Future uses that will require considerable planning and may sacrifice part of the waste disposal purpose are all those concerning roads and utilities and those involving the foundation of structures (Figure 102). The following foundation types are generally required for increasingly heavier structures:

a. Mat foundation.

b. Spread footings.

c. Pile foundation.

d. Piers or caissons.

The reader is referred elsewhere[3,138,139] for recommendations on mats, deep foundations, utilities, and other structural aspects since these subjects exceed the scope of this manual.

DESIGNING FOR FUTURE USE

Perhaps the best cover design measure in preparation for the future use

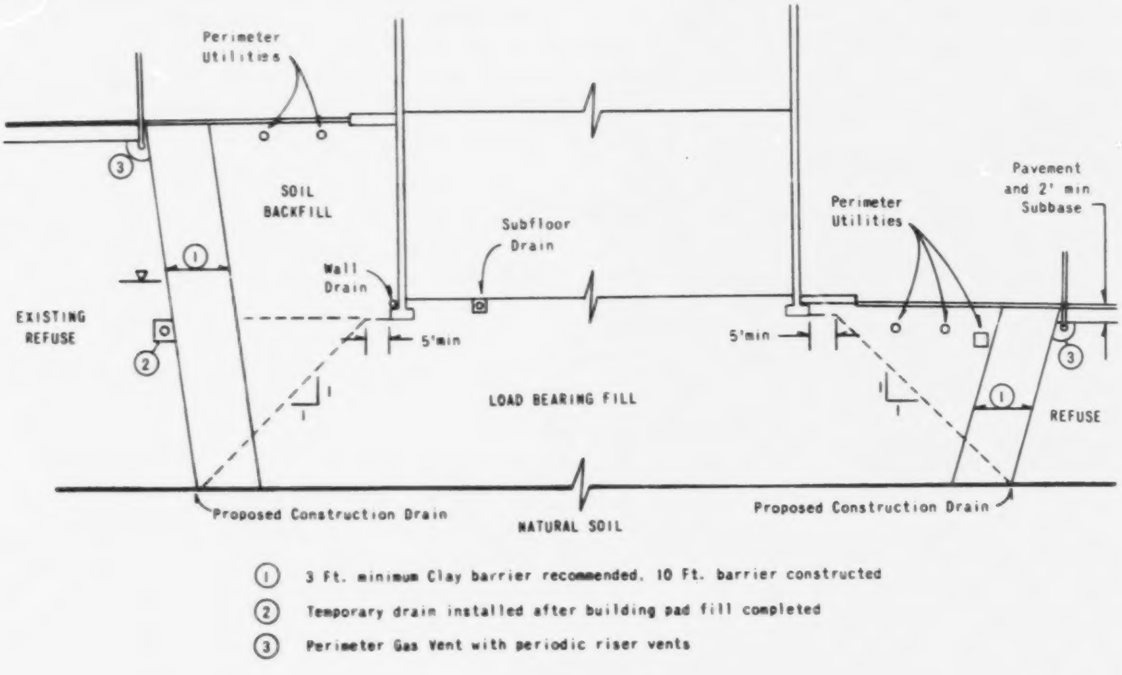
Perimeter Utilities
③
SOIL BACKFILL
①
②
EXISTING REFUSE
Wall Drain
Subfloor Drain
5'min
5'min
1
1
LOAD BEARING FILL
Perimeter Utilities
Pavement and 2' min Subbase
③
①
REFUSE
1
1
Proposed Construction Drain
NATURAL SOIL
Proposed Construction Drain
① 3 Ft. minimum Clay barrier recommended. 10 Ft. barrier constructed
② Temporary drain installed after building pad fill completed
③ Perimeter Gas Vent with periodic riser vents

Figure 102. Foundation design for building at old sanitary landfill.[138]

of a landfill of solid or hazardous waste is to know before the operation begins what the eventual use will be. Ideally, this information would include surveyed locations of structures requiring significant support, recreational facilities requiring specific topography, and such details as the load anticipated on parking lots. Where such preparations have not been made, the site may require extensive renovation before it can be used.

Increased Cap Thickness

The low bearing capacity of a sanitary landfill can be circumvented by increasing the soil thickness above waste.[139] In this way, the strong soil resists both punching and rotational shear. The thickness of soil should be at least 1.5 times the width of structural footings.

Increased Cover/Waste Ratio

Reduction in the overall amount of spongy waste (versus daily cover) in a landfill will also improve the supportive capability as a foundation.[3] At some ratio not much below the common 3:1 waste to soil, the efficiency of the landfill for disposal of solid waste becomes unacceptably low. This conflict is one reason for recommending careful planning. It may be that sacrifice of disposal space is only needed immediately below the intended foundation as discussed below.

Compaction

Beneficial effects of compaction on strength, permeability, and secondary characteristics, such as erodibility, have been discussed elsewhere. Field compaction should be planned and incorporated into specifications for the landfilling operation. It will also be advisable to have such quality control during construction that the design compaction conditions are achieved.

Additives and Cements

Another technique worth consideration is the incorporation of stabilizers into the soil during cover placement. Common chemicals mixed with soil include lime, portland cement, and numerous organic chemicals. The desired effect may be strengthening by cementation, waterproofing, or dispersion for greater density and lower permeability. Wetting, mixing, compacting, and curing are all critical steps[140] and achieving a homogeneous and uniform mixture is not so simple.

Selective Disposal

Consider placing and compacting waste suitable for foundations in areas (pads) to support planned buildings. For example, fly ash and bottom ash may be compacted in 1-ft lifts in assigned areas while other solid waste is distributed elsewhere in adjacent areas. This method is the extreme case of Increased Cover/Waste Ratio.

Undisturbed Structural Pads

Leaving pedestals of undisturbed ground as structural pads solves the problem of providing foundations for future buildings in sanitary landfilling operations.

Dewatering Layers

Drainage layers placed originally as cover may facilitate and hasten the consolidation of saturated solid waste. Such a system might consist of 1-ft sand layers connected to gravity drains as discussed in Section 15.

The settlement process may be accelerated under certain conditions of groundwater circulation and solid waste degradation. It was observed in one full-scale field test[29] that settlement increased with removal and recirculation of leachate through the waste cells. Faster settlement apparently resulted from the increase in decomposition rate.

Preloading

Preloading involves densification by placing a temporary surcharge of soil. Preloading might be a useful landfill preparation when:

a. Soil or other material is readily available for use as preload.

b. Time for stabilization is short.

c. Only minor additional decomposition is anticipated.

A program of careful monitoring of the settlement under the preload is essential. Only after a satisfactory decrease in the settling rate is established would it be feasible to remove the preload and build the structure. Even then, settlement may continue if waste decomposition continues.[3]

Backfilling and Replacement

Where the future use of a landfill is not specifically identified, a more practical approach may be to postpone foundation improvement until plans for usage are firmed up. At such time, the landfill can be excavated immediately at the planned foundation and backfilled with suitable granular material that drains well and is low in frost susceptibility. Pipe drains at the perimeter of the foundation should also be provided.

The extra cost of granular materials from outside the site may necessitate the use of some of the excavated waste in fills for roadways[104] and light structure foundations. In such case one should blend soil into aged waste to 50 percent or more. No layer of the refuse/soil mixture should be within 4 ft of finished grade.

Excavation and backfilling may require safeguards against disturbing a stabilized condition or exposing the buried solid waste as a health hazard. It may be necessary, for instance, to line the backfill area with impervious clay to prevent an inflow of leachate or gas into the granular foundation. In any case, initial excavation should proceed with due concern for H_2S and CH_4.

Gas Channels and Vents

A common difficulty is keeping landfill gases from accumulating in the structure. Even buildings erected on undisturbed soil pads must be specially designed to prevent such accumulation. A layer of sand can be laid over the proposed structural area and then be covered by two or more membranes.[139] An additional layer of sand above protects the membranes. Gas is thus blocked from the structure and can migrate laterally to vents at convenient locations.

Utility connections must be made gas-proof if they enter a structure below grade. If the building is surrounded by filled land, utility and sewage lines that traverse the fill must be flexible, and slack should be provided so that the lines can adjust to settlement without breaks or low spots.

Remedial Grouting

Occasionally, additives should be considered to stabilize the foundation portion of the landfill and improve its supportive qualities. Additives may be spread, worked into the cover soil, or injected into the cover and waste cells below. The labor cost for injection may be quite high; it was estimated several years ago that labor and material cost ranged between 25 and 100 dollars/yd^3 of treated soil.[140]

A grout composed of soil, cement, and water is sometimes used to fill voids in dumped stone deposits and, by analogy, may be suitable for filling voids in interlayered solid waste and cover soil. Various types of chemical grouts are available. Those chemical grouts with relatively low viscosity may be capable of penetrating the soil pore structure to provide cementation. Sodium silicate is used for this purpose, but its permanence is questionable. On aging, the silicic gel shrinks and cracks and may be dissolved under alkaline conditions. Certain fixative chemicals or physical stabilizers convert sludge waste to nontoxic, load-bearing material.[29]

Pile and Pier Foundations

Where other means of achieving a supportive foundation on a solid waste landfill are unsuccessful, a system of piles or piers can be used to support important structures. Even with these extreme measures, problems may not be entirely eliminated. The landfill may continue to settle around and away from the stable structure and incidentally cause the piling to take additional, unanticipated loads through mobilization of negative skin friction. Figure 103 shows schematically the surface settlement observed in one landfill-related problem; incidently, methane generation and migration had compounded the problem.

Documentation

The most cost-effective technique for future use may be to build a permanent file of information on the configuration, content, and history of the

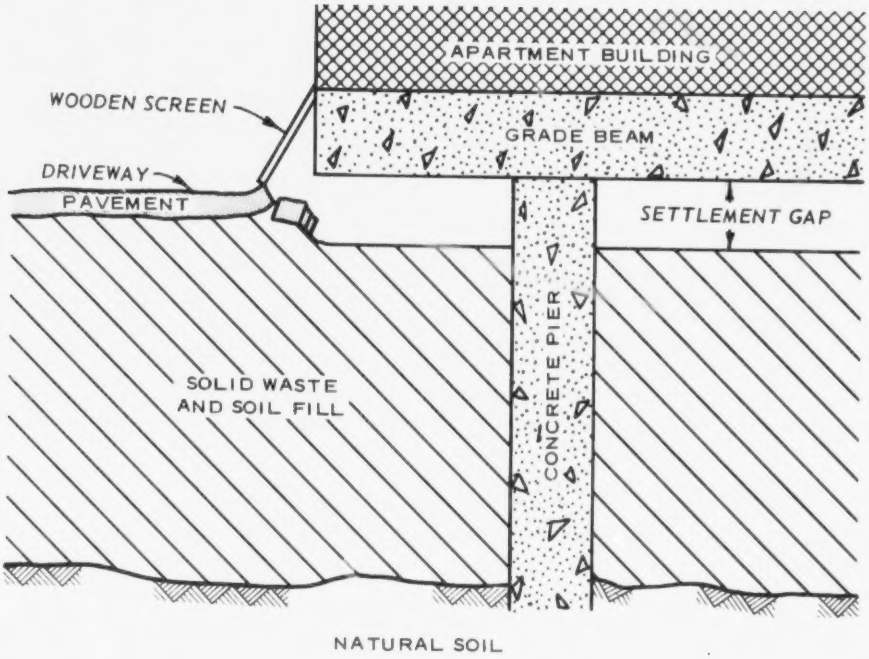
APARTMENT BUILDING
WOODEN SCREEN
GRADE BEAM
DRIVEWAY
PAVEMENT
SETTLEMENT GAP
CONCRETE PIER
SOLID WASTE AND SOIL FILL
NATURAL SOIL

Figure 103. Settlement of solid waste beneath and around building founded on piers.

landfill. Accurate topography for the base of waste alone will, in combination with ultimate surface topography, provide invaluable engineering background and may make expensive borings unnecessary. Information on settlement, erosion, and concentrations and timing of leachate will also be useful later. The planner should consider requiring such a record from the operator with provisions for placing a short description (with accurate location map) on public record.

Maintenance

Provisions for maintenance after site closure should follow a logical plan according to future use. Some cover deterioration like erosion can be tolerated where the future use plan has inherent provisions for repair maintenance, e.g., at a landfill converted to a golf course. On the other hand, maintenance of cover may not be practical where the site is remote and no further active use is planned. In such cases, it is necessary to design the cover more conservatively to avoid serious deterioration in the future.

SECTION 23

SUMMARY EXAMPLE

This manual provides guidance on covering solid waste by reviewing the various factors affecting the satisfactory performance of cover and by making numerous recommendations for effective selection and placement. The following hypothetical example should serve to illustrate how the manual may be used on a specific site problem.

The hypothetical example is a municipally owned and operated sanitary landfill in a small city. Household and commerical waste will form the bulk of the incoming solid waste, but small amounts of industrial waste will be accepted. The location of the landfill has been established by preliminary investigation. The landfill will eventually be converted to a nature strip and park serving subdivisions that are anticipated to develop on both sides of the fill in the future.

The only materials available in abundance in this region have been found previously to be the natural silty soil that reaches thicknesses of 20 ft and sand and silt mixtures available as a by-product of washed gravel operations in the vicinity. A third material, available in lesser quantity, is relatively stiff clay exposed in active gravel pits at the base of the gravel-bearing stratum. This clay is not used otherwise and would have to be excavated.

On the basis of existing test results or the results of new tests for the study, the three possible cover materials are determined to be of USCS types SP, ML, and CH. The water content for the SP varies considerably since this soil drains well. The ML contains about 20 percent water as excavated, and the CH soil commonly contains about 25 percent water.

The preliminary investigations are completed, and a preliminary design is prepared for the final topographic configuration. Various constraints are imposed, e.g., at least a 5-ft buffer of undisturbed soil must intervene between the base of solid waste and the highest position of the phreatic surface. As a first step in designing a cover and choosing appropriate material, the city engineer in cooperation with the city planner establishes the priorities of functions of the cover.

The city engineer prepares the following tabulation for displaying effectiveness of the three soils in the six most important cover functions (in order of priority). Other cover functions are considered subordinate in this example.

Cover Function	SP	ML	CH
Impede infiltration of water	IX	IV	I
Control bird population by reducing attractiveness to birds	--	--	--
Control wind erosion of soil	II	VII	X
Limit gas migration*	VII	III	I
Control water erosion of soil	II	XIII	IX
Assure trafficability	I	IX	VI
All other functions (approximately equally important)			

The most favorable rating is I. Clearly, the SP and CH soils have distinct advantages in certain functions. The SP soil is rated I for trafficability and II for water and wind erosion control. The CH soil has its advantages in impeding water percolation and gas migration. The ML soil is rated between the other two in all functions except trafficability, where it is rated poorer than both.

As a next step, a cost analysis is performed, and it is quantitatively determined that considerable expense will be incurred in importing SP and CH. Existing equipment can accomplish all excavation and transportation of indigenous ML soil, and therefore, cost of using this soil (beyond the on-site costs comparable to using stockpiled SP or CH) will be negligible. This large advantage convinces the city that the ML soil on the site should be used.

After the decision is made to use ML soil, certain operational procedures must be established to improve somewhat marginal soil qualities. The ML soil, though rated a modest IV, has a permeability of approximately 10^{-5} cm/sec that should adequately impede percolation and gas leakage during the relatively short exposure of daily and intermediate covers. For the final cover, however, a 6-in. layer of compacted CH should be incorporated at the bottom for added resistance to percolation and gas migration. A system of gravel-filled trenches will safely vent to the atmosphere.

To hold water erosion to an acceptably low level, an operational plan of compacting cover is recommended even for daily cover. Arrangements should also be made to use large stockpiles of gravel and SP soils as additions to daily cover whenever rainfall threatens to reach an amount established previously as excessive. Long-range measures for protecting the final cover from both wind and water erosion are a program of rapid topsoil restoration and seeding for vegetation. A stabilizing additive and/or a thin covering of SP soil from the stockpile can be specified as needed to prevent excessive wind erosion in the short range.

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* A rating of I indicates that gas will not tend to move through the soil but will tend to seek an alternative direction of travel.

The remaining cover function given special consideration is trafficability. The ML soil has deficiencies in this function, so two operational procedures are recommended. First, the main access should be routed on permanent, all-weather gravel roads along both boundaries with short branches as needed to the working area. Second, a special area should be reserved for wet-period operations. These detailed considerations having beneficial effects on trafficability and the other principal functions discussed above are finally formalized in specifications or in plans for operation, closure, and maintenance. The development of the disposal area (in regard to cover) will then proceed in an orderly, efficient manner.

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